the Waffle®

An Innovative Approach to Flood Mitigation in the Red River Basin: The Final Results and Conclusions of the Waffle Project

EERC
Energy & Environmental Research Center®
UND University of North Dakota
Grand Forks

AN EVALUATION OF BASINWIDE, DISTRIBUTED STORAGE IN THE RED RIVER BASIN: THE WAFFLE® CONCEPT

Final Report

(for the period April 5, 2002, through December 31, 2006)

Prepared for:

U.S. Department of Agriculture
Natural Resources Conservation Service
PO Box 1458
Bismarck, ND 58502

USDA NRCS Grant Agreement No. 69-6633-2-4

Prepared by:

Bethany A. Kurz
Xixi Wang
Lynette de Silva
Sheila K. Hanson
Marc D. Kurz
Wesley D. Peck
Troy K. Simonsen
Edward N. Steadman

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

December 2007

EERC DISCLAIMER

LEGAL NOTICE This research report was prepared by the Energy & Environmental Research Center (EERC), an agency of the University of North Dakota, as an account of work sponsored by U.S. Department of Agriculture Natural Resources Conservation Service Grant Agreement No. 69-6633-2-4. Because of the research nature of the work performed, neither the EERC nor any of its employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement or recommendation by the EERC.

ACKNOWLEDGMENTS

The Energy & Environmental Research Center (EERC) gratefully acknowledges the following individuals, organizations, and agencies that enabled the evaluation of the Waffle® concept. First and foremost, the EERC would like to recognize the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS), the funding source for this study. In addition, the EERC greatly appreciates the time and effort contributed by the members of its Agency and Citizens Advisory Boards. Their input and guidance were an invaluable contribution to this project. The project team is also greatly appreciative of the peer review, guidance, and input of EERC Associate Director for Research John Harju.

The Waffle project team would also like to express its sincere gratitude to the following individuals for their constructive input and guidance: Mr. William Schuh (North Dakota State Water Commission), Scott Jutila (U.S. Army Corps of Engineers), Stuart Dobberpuhl (U.S. Army Corps of Engineers), Randy Gjestvang (North Dakota State Water Commission), Tim Fay (North Dakota State Water Commission), James Schmidt (NRCS), Dennis Reep (NRCS), Dave Hagert, Jerry Moran, John Scott, Dale Stenerson, and John Younggren. The Waffle project team is also grateful to those advisory board members who reviewed the draft final report and provided input.

The EERC expresses its sincere gratitude to Senator Byron Dorgan, who recognizes that long-term security from flooding is vital to the economic vitality of our region. The evaluation of this concept would not have been possible without his support.

In addition to the authors listed on this report, the following individuals deserve recognition for their contributions to this effort: Barry Botnen, Doug Davidson, Kim Dickman, Heith Dokken, James Johnson, Kerryanne Leroux, Stephanie Nielson, Sarita Pachhai, and Kirk Williams (EERC); Dean Bangsund, Eric DeVuyst, and F. Larry Leistritz (North Dakota State University); and Andrew Manale (U.S. Environmental Protection Agency).

A special thank you goes to Daniel Stepan (EERC) and James Evans (EERC) for providing in-depth review of this document.

The project team would also like to express its sincere appreciation to EERC Director Gerald Groenewold for his vision, dedication, and passion for the Waffle concept.

Leaders establish the vision for the future and set the strategy for getting there; they cause change. They motivate and inspire others to go in the right direction and they, along with everyone else, sacrifice to get there. – John Kotter

The first step toward creating an improved future is developing the ability to envision it. – Author Unknown

Waffle Project Advisory Board Members

The EERC gratefully acknowledges the input and guidance provided by the following members of the Agency Advisory Board and the Citizens Advisory Board:

Agency Advisory Board Members

Donald Elston
Red River Joint Water Resource Board
Hope, North Dakota

John Giedt
U.S. Environmental Protection Agency
Region 8
Denver, Colorado

Randy Gjestvang
North Dakota State Water Commission
West Fargo, North Dakota

Robert Gleason
U.S. Geological Survey
Jamestown, North Dakota

Bob Harrison
Manitoba Conservation
Winnipeg, Manitoba

Roger Hollevoet
U.S. Fish and Wildlife Service
Devils Lake, North Dakota

Scott Jutila
U.S. Army Corps of Engineers
St. Paul, Minnesota

Glen Kajewski
NRCS
Area 1 Office
Thief River Falls, Minnesota

Citizens Advisory Board Members

David Burkland
Grand Forks, North Dakota

Leon Dubourt
Walhalla, North Dakota

Dave Hagert
Emerado, North Dakota

Dwayne Johnston
Grand Forks, North Dakota

Ron Klevberg
Northwood, North Dakota

Lonnie Leake
Emerado, North Dakota

Bob Lebacken
Grand Forks, North Dakota

Mary Loyland
Thompson, North Dakota

Sam Martinson
Grand Forks, North Dakota

Jerry Moran
Grand Forks, North Dakota

Michael Polovitz
Grand Forks, North Dakota

Gerry Porath
Grand Forks, North Dakota

John Scott
Gilby, North Dakota

Agency Advisory Board Members

Linda Kingery
Northwest Sustainable Development Partnership
Cavalier, North Dakota

Ruth Lewis
Red River Basin Commission
Moorhead, Minnesota

John Liou
Federal Emergency Management Agency
Denver, Colorado

Leon Osborne
Regional Weather Information Center
Grand Forks, North Dakota

G. Padmanabhan
North Dakota State University
Fargo, North Dakota

Mike Sauer
North Dakota Department of Health
Bismarck, North Dakota

James Schmidt
U.S. Department of Agriculture
Natural Resources Conservation Service
Bismarck, North Dakota

Bill Schuh
North Dakota State Water Commission
Bismarck, North Dakota

Jim Solstad
Minnesota Department of Natural Resources
Waters Division
St. Paul, Minnesota

Citizens Advisory Board Members

Dale Stenerson
Fargo, North Dakota

Don Vellenga
Ada, Minnesota

Jack Waters
Grand Forks, North Dakota

John Younggren
Hallock, Minnesota

Agency Advisory Board Members

Gary Thompson
Red River Joint Water Resource Board
Mayville, North Dakota

Genevieve Thompson
Audubon Dakota
Fargo, North Dakota

Mike Vavricka
Minnesota Pollution Control Agency
Detroit Lakes, Minnesota

Esther Vogel
North Dakota Department of Transportation
Design Division
Bismarck, North Dakota

Jeffrey Volk
Moore Engineering
West Fargo, North Dakota

Dean Wieland
CPS Ltd.
Grand Forks, North Dakota

TABLE OF CONTENTS

Continued . . .

TABLE OF CONTENTS (continued)

Continued . . .

TABLE OF CONTENTS (continued)

LIST OF FIGURES

Continued . . .

LIST OF FIGURES (continued)

Continued . . .

LIST OF FIGURES (continued)

Continued . . .

LIST OF FIGURES (continued)

Continued . . .

LIST OF FIGURES (continued)

LIST OF TABLES

Continued . . .

LIST OF TABLES (continued)

Continued . . .

LIST OF TABLES (continued)

NOMENCLATURE

AAB	Agency Advisory Board
ACS	American Crystal Sugar Company
ARS	Agricultural Research Service
ATV	all-terrain vehicle
BMP	best management practices
CAB	Citizens' Advisory Board
CDA	County Ditch Authority
CREP	Conservation Reserve Enhancement Program
CRP	Conservation Reserve Program
CSP	Conservation Security Program
DNR	Department of Natural Resources
DOQ	digital orthophoto quadrangle
DOT	Department of Transportation
DRG	digital raster graphics
EERC	Energy & Environmental Research Center
EPA	U.S. Environmental Protection Agency
EQIP	Environmental Quality Incentive Program
FAQs	frequently asked questions
FCIC	Federal Crop Insurance Corporation
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FOTG	Field Office Technical Guide
FSA	Farm Service Agency
GIS	geographic information system
GPS	global positioning system
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling System
HRU	hydrologic response unit
HUC	Hydrologic Unit Code
IJC	International Joint Commission
IRB	Institutional Review Board
Lidar	light detection and ranging
LULC	land use and land cover
MNDOT	Minnesota Department of Transportation
NASS	National Agricultural Statistics Service
NCDC	National Climate Data Center
NCHRP	National Cooperative Highway Research Program
NDSU	North Dakota State University
NED	National Elevation Dataset
NHD	National Hydrography Dataset
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
PCB	polychlorinated biphenyl

PLSS	Public Land Survey System
PVC	polyvinyl chloride
RAS	River Analysis System
RMA	Risk Management Agency
RRB	Red River Basin
SAR	Sodium Adsorption Ratio
STATSGO	State Soil Geographic Database
SWAT	Soil and Water Assessment Tool
TPEL	targeted protection elevation
TRIS	Transportation Research Information Services
UMAC	Upper Midwest Aerospace Consortium
UND	University of North Dakota
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WSEL	water surface elevation

AN INNOVATIVE APPROACH TO BASINWIDE FLOOD CONTROL: THE EVALUATION OF THE WAFFLE® CONCEPT

EXECUTIVE SUMMARY

This document marks the culmination of a multiyear study to evaluate the feasibility of employing a basinwide, distributed, temporary storage strategy as a means of augmenting existing dikes and controlling the devastating effects of springtime flooding in the Red River of the North Basin (RRB). With funding provided by the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS) and input and guidance from two advisory boards, the Energy & Environmental Research Center (EERC) evaluated the feasibility of utilizing a basinwide system for temporary storage of floodwater in the RRB. The flood mitigation approach, referred to as the Waffle concept, could be accomplished by temporary storage of springtime runoff in existing "depressions" within the basin, primarily ditches and low-relief fields bounded by existing roads. The storage areas, roads, and existing drainage systems could act as a distributed network of channels and control structures for the temporary storage and controlled release of the retained water to reduce peak flood crests along the Red River and its tributaries.

In order to evaluate the efficacy of the Waffle concept, it was necessary to 1) determine if sufficient storage capacity is present in the RRB to provide significant mitigation of major springtime floods; 2) develop a comprehensive combined hydraulic/hydrologic model of the Red River drainage basin to evaluate the flood mitigation benefits of Waffle storage during floods of various magnitude; 3) evaluate the impacts of temporary Waffle storage on downstream flood reduction and on the landscape through multiple field trials; 4) examine the economic feasibility of the Waffle concept to mitigate large springtime floods, including the costs of implementation, administration, and maintenance, as well as the benefits of mitigating flood damages; and 5) evaluate stakeholder receptivity to the concept.

Simulated effects of the Waffle vary widely over the RRB and with different event scenarios. For one 1997 flood scenario, the largest simulated reduction in peak flood stage (as much as 6.2 feet) occurred in Fargo, North Dakota, and the least reduction (as little as 0.2 feet) occurred in Wahpeton, North Dakota. Numerous field trials conducted over the course of the study verified the effectiveness of the concept for flood mitigation and suggested that the Waffle approach can reduce overall flood volumes through increased evaporation and infiltration, increase soil moisture, and supplement groundwater reserves without adversely affecting the environment. The predicted flood mitigation benefits for several larger communities along the Red River as well as the estimated cost of implementing the Waffle were used to determine the net economic benefit of the concept. The estimated net benefit of Waffle implementation over the next 50 years was on the order of hundreds of millions of dollars, with some implementation scenarios exceeding $800 million in benefits. The averted flood damages from Fargo/Moorhead dominated the economic benefits of the Waffle for the larger communities along the Red River. While the economic benefits of the Waffle estimated herein may be sufficient to warrant evaluation of implementation options, there are additional unquantified economic benefits associated with avoided flood damage to smaller communities, agricultural land, rural infrastructure (i.e., roads and culverts), and farmsteads.

The results of this study indicate that the Waffle concept is a viable means of mitigating damage from large springtime floods. The Waffle approach is particularly effective as a means of intercepting, controlling, and reducing overland runoff and, as such, offers an excellent augment to on-channel dams, dikes, or diversions, which address channel flow, not overland runoff. And unlike conventional structural measures, the Waffle approach does not entail implementing drastic structural measures to intercept, retain, or divert large volumes of water in order to achieve flood mitigation benefits—instead minor structural modifications are made to existing culverts to retain precipitation primarily where it falls on the landscape. In addition, by controlling and temporarily storing overland runoff, the Waffle approach offers several ancillary benefits, including reduced sediment erosion from the landscape and within waterways and increased soil moisture and groundwater recharge during dry years.

The Waffle approach not only provides a significant augment to conventional flood mitigation measures, but it would help to safeguard those areas with limited or no flood protection measures, such as agricultural lands, farmsteads, smaller communities, and rural infrastructure. Because the Waffle concept need not be implemented on a basinwide scale to provide local benefits, it allows for flexibility with implementation guidelines and policies, which can be developed to best suit the needs of participants and beneficiaries within a particular region. In addition, implementation of the concept on a subwatershed-by-subwatershed basis with a focus on local damage mitigation may facilitate realization of the concept throughout the entire RRB.

In addition to establishing the viability of the Waffle concept, this project developed several water management tools that will benefit stakeholders for decades to come, including the first comprehensive hydraulic/hydrologic model of the entire RRB. These models can be used to investigate the effects of a variety of structural and nonstructural flood mitigation practices and/or land management practices on water quantity and water quality throughout the RRB.

Given the history of severe and frequent flooding in the region, a basinwide flood mitigation approach like the Waffle is needed to provide long-term security from floods and, in turn, the economic vitality of the region. The results of this study have shown that coordinated basinwide water management is viable, and the Waffle concept is a marvelous example of an approach available for implementation.

PROJECT SUMMARY

Introduction and Background

The purpose of this study was to determine the overall feasibility of employing a basinwide, distributed, temporary storage strategy as a means of controlling the devastating effects of springtime flooding in the Red River of the North Basin (RRB). Floods are the most common and costly large natural disturbances affecting the United States and account for nine of every ten presidential disaster declarations (Haeuber and Michener, 1998). The RRB is subject to frequent damaging inundation from minor and major flood events. Since official record keeping began in 1882, major floods affecting large areas of the basin have occurred once in about every 4 to 6 years, with a truly devastating flood about every decade (LeFever et al., 1999; International Joint Commission, 1997). The 1997 flood resulted in approximately $5 billion in damages to the RRB (International Joint Commission, 2000) and underscored the need for exploration of innovative concepts to augment existing flood mitigation measures. Implementation of cost-effective solutions to mitigate damage from devastating floods is critical for the economic stability of the region.

To address the need for innovative flood mitigation measures, the Energy & Environmental Research Center (EERC) evaluated the feasibility of utilizing a basinwide system for temporary storage of floodwater in the RRB to help mitigate large springtime floods such as the 1997 flood of record. The flood mitigation effect, referred to as the Waffle concept, would be accomplished utilizing existing "depressions" within the basin, primarily ditches and low-relief fields bounded by existing roads, for temporary storage and controlled release of springtime runoff. The storage areas, roads, and drainage structures would act as a network of channels and control structures to temporarily store water until the Red River flood crest passes. Although by no means a natural system, the Waffle would work with existing infrastructure to mimic a natural system by slowing the progress of water to the Red River. The Waffle concept addresses excess runoff before it enters the streams and rivers of the RRB and becomes a problem, thereby lessening the volume of water needed to be retained by dikes or redirected by downstream diversions.

In order to evaluate the efficacy of the Waffle concept, it was necessary to 1) determine if sufficient storage capacity is present in the RRB to provide significant mitigation of major springtime floods; 2) develop a comprehensive combined hydraulic/hydrologic model of the Red River drainage basin to evaluate the flood mitigation benefits of Waffle storage during floods of various magnitude; 3) evaluate the impacts of temporary Waffle storage on downstream flood reduction and on the landscape through multiple field trials; 4) determine the economic feasibility of the Waffle concept to mitigate large springtime floods, including the costs of implementation, administration, and maintenance, as well as the benefits of mitigating flood damages; and 5) determine if landowners, agencies, and other stakeholders would be receptive to the implementation of such a plan.

The results of this study indicate that the Waffle plan is a technically, economically, and socially feasible means of springtime flood mitigation. In addition, the Waffle approach has the potential to provide numerous ancillary benefits such as reduced soil erosion and sedimentation in streams and rivers, increased soil moisture in agricultural soils during dry years, and groundwater recharge, as well as positive effects on the economy as a result of providing additional security from devastating springtime floods. The Waffle plan would be a very beneficial part of a sustainable, overall watershed management strategy, and the plan could be successfully implemented if the people of the RRB choose to do so. In addition to establishing the viability of the Waffle concept, the project produced several water management tools that will benefit stakeholders for decades to come including the first comprehensive hydraulic/hydrologic model of the entire RRB, an interactive, online database containing natural resource-related metadata for the RRB, an online database containing over 400 literature resources related to RRB flooding, and a compilation of landowner/producer opinions regarding flooding and the most socially acceptable means of flood mitigation. The following provides a summary of specific conclusions.

Distributed Storage Capacity

Two storage volume estimates were determined for use in estimating the potential flood mitigation effect: a conservative storage estimate of 583,400 acre-ft, which took into account larger reductions for freeboard and natural storage, and a more moderate storage estimate of 2,188,400 acre-ft, which assumed smaller-volume reductions to account for freeboard and natural storage. These volume estimates assume that water storage occurs on land surrounded by existing roads; however, the results also indicate that dispersed storage volumes could be significantly increased (perhaps doubled or tripled) if the lowest points along the roads surrounding storage sections were raised by 1 or 2 feet.

Based on the conservative and moderate storage volume estimates and the average depth of water contained in individual storage sections, an estimated 334,200 to 1,170,500 acres of land would be temporarily flooded during the spring if the Waffle were fully implemented. This corresponds to 1.5% to 5.2% of the RRB total land area (excluding the Devils Lake Basin). The estimates of flooded acreage were scaled up to provide an estimate of payment acreage by county for consideration in the economic analysis. Payment acreage represents the estimated land area that a participant in the Waffle Program would likely be reimbursed for and includes not just flooded acreage, but acreage that may have restricted access as a result of water storage. The total estimated payment acreage ranges from a minimum estimate of approximately 405,300 acres to a maximum estimate of approximately 1,414,600 acres, equivalent to 1.7% and 6.1%, respectively, of the total RRB land area (excluding the Devils Lake Basin).

Estimated Flood Reduction Impacts of Waffle Storage

The Waffle storage volume estimates determined in this study were modeled using the Soil and Water Assessment Tool (SWAT) and the Hydrologic Engineering Center's River Analysis System (HEC–RAS) to evaluate peak flow reductions in the Red River and its tributaries and peak stage reductions along the Red River. The results from the model evaluation indicate that Waffle storage could significantly reduce peak stream flows and stages during major springtime flood events. The SWAT model results predicted that conservative Waffle storage volumes could reduce 1997-magnitude peak flows along the tributaries by an average of 13%, with a range from less than 1% to as high as 59.2%. The moderate Waffle storage volumes were estimated to reduce 1997-type peak flows by an average of approximately 33%, with a range from 6% to 96%.

The peak flow reductions along the tributaries were used as input into the HEC–RAS model to determine peak flow and stage reductions along the Red River as a result of implementing Waffle storage during a 1997-type flood event. In addition to the 1997 flood, several hypothetical flood events with flows smaller or larger than 1997 were evaluated, including 50%, 125%, 150%, and 200% of 1997 flows. Estimated stage reductions for the various flood events and Waffle storage volumes ranged from 0 to 2.43 feet at Wahpeton–Breckenridge; 2.4 to 7.7 feet at Fargo–Moorhead; 0.1 to 9.2 feet at Grand Forks–East Grand Forks; and 0.2 to 3.7 feet at Drayton. For a 1997-type flood, the estimated stage reductions as a result of implementing 100% of moderate and conservative Waffle storage volumes, respectively, ranged from 0.3 to 2 feet at Wahpeton–Breckenridge, 3.6 to 6.2 feet at Fargo–Moorhead, 2 to 5 feet at Grand Forks–East Grand Forks, and 1 to 2.4 feet at Drayton. Overall, the largest reductions were estimated for floods with 50% of 1997 flows if 100% of the moderate storage volumes (~2,188,400 acre-ft) were implemented, and the lowest reductions were estimated for floods with 200% of 1997 flows if only 50% of the conservative Waffle storage volumes (~259,000 acre-ft) were implemented.

Field Trial Results

The Waffle field trials were conducted to verify downstream reductions in flooding as a result of upstream storage in Waffle sections and to determine the effects of extended springtime water storage on the land. The field trial assessments of the Waffle concept provided an evaluation of both its effectiveness as a flood mitigation measure and the potential impacts of water storage on the environment, roads, and agriculture. Through water quality and soil chemistry analyses the EERC determined that temporary storage of water through the Waffle concept had minimal impacts on the land and the environment. During the 2-year experiment period, crop yield estimates indicated that there were no adverse impacts to the production of sunflowers or corn with the observed 5-day delay in planting as a result of the extended water storage. Evaluation of road stability indicated that sufficiently—thick frost lenses are present within roadbeds during water storage to limit infiltration and preserve road stability.

Water loss in the storage parcels due to infiltration and evaporation was significant, averaging 38% of the total storage volume. This indicates that the Waffle could not only slow overland runoff and reduce peak flow rates, but it could also help reduce the overall volume of floods. The infiltration of water to the subsurface could also play a key role in helping to increase soil moisture and recharge groundwater supplies during periods of drought. This is supported by the fact that soil moisture was maintained at higher levels longer into the growing season on the flooded portions of the field trial parcels.

Stakeholder Receptivity to the Waffle Plan

Specific recommendations based on public input, issues and concerns, and items that should be taken into account or addressed prior to Waffle implementation include the following:

- Participation in the Waffle Program should be voluntary.

- Participation in the Waffle Program will be greatest if compensation is provided to the landowner to offset the perceived risk of extended water storage.

- The public is most supportive of Waffle storage on public land or in conjunction with the Conservation Reserve Program, administered by the Farm Service Agency.

- Special arrangements should be made with participating producers that grow contract crops, such as sugar beets and potatoes, in the event that planting deadlines are not met.

- Additional arrangements may also need to be made with Waffle participants in the event that final planting dates established through the federal crop insurance program are not met.

- A single committee, group, or agency should be responsible for coordination of Waffle storage and release during a major flood year. This committee should work with local entities to ensure that the storage is implemented as planned.

- Prior to implementation, educational public meetings should help at the local level to explain the approach and to address landowner and stakeholder concerns regarding the operational aspects of Waffle storage.

- Prior to large-scale implementation of the Waffle concept, North Dakota and Minnesota stream-crossing statutes and rules within the Department of Transportation must be modified to allow for the use of roads for Waffle storage during the spring.

Economic Analysis

Results of the economic analysis suggest that the Waffle would offer significant economic benefits if used to mitigate large spring floods for the major cities of the RRB. Net benefits of the Waffle, if implemented over the next 50 years, ranged from $125–$707 million using average (baseline) cost projections. In most cases, over 80% of the flood mitigation benefits for the larger communities along the Red River were from Fargo/Moorhead.

It is important to note that the potential environmental benefits and flood mitigation benefits to smaller communities, farmsteads, and rural infrastructure and agricultural land were beyond the scope of this study; however, mitigation of these damages could be significant. For example, during major spring floods, it is not uncommon for individual counties to spend upwards of $1 million to repair damaged roads (personal communication, Grand Forks County Highway Department, 2006). In addition, most landowners and/or producers are powerless to prevent their fields from being flooded from upstream runoff. The Waffle could provide a means of reducing unintentional flooding of agricultural land, while providing payments to landowners that agree to temporarily store water on their land. In addition, potential ancillary benefits, such as reduced sediment transport in the RRB waterways and increased soil moisture and aquifer recharge during droughts, could also be significant.

Conclusions

The results of this study indicate that the Waffle concept is a viable means of mitigating damage from large springtime floods. The Waffle approach is particularly effective as a means of intercepting, controlling, and reducing overland runoff and, as such, offers an excellent complement to on-channel dams, dikes, or diversions, which address channel flow, not overland runoff. And unlike conventional structural measures, the Waffle approach does not entail implementing drastic structural measures to intercept, retain, or divert large volumes of water in order to achieve flood mitigation benefits—instead minor structural modifications are made to existing culverts to retain precipitation where it fell on the landscape. The Waffle approach not only provides a necessary augment to conventional flood mitigation measures, but it would help safeguard those areas with limited or no flood protection measures, such as agricultural land, farmsteads, and smaller communities. Given the history of severe and frequent flooding in the region, a basinwide flood mitigation approach like the Waffle is needed to provide long-term security from floods for the economic stability of the region.

References

Haeuber, R.A., and Michener, W.K., 1998, Issues in Science and Technology, p. 74–80.

International Joint Commission, 1997, Red River Flooding—Short-Term Measures: Interim report of the International Red River Basin Task Force to the International Joint Commission, Ottawa – Washington, 65 p.

International Joint Commission, 2000, Living with the Red: A report to the Governments of Canada and the United States on Reducing Flood Impacts in the Red River Basin, 82 p.

LeFever, J.A., Bluemle, J.P., and Waldkirch, R.P., 1999, Flooding in the Grand Forks–East Grand Forks – North Dakota and Minnesota Area: North Dakota Geological Survey Educational Series 25, 63 p.

AN INNOVATIVE APPROACH TO BASINWIDE FLOOD CONTROL: THE EVALUATION OF THE WAFFLE® CONCEPT

1.0 THE WAFFLE CONCEPT

1.1 Introduction

The pioneers who opened up the central interior of North America found a region of unprecedented agricultural potential. The deep rich soils eventually provided the raw material that would feed our growing nation and the world. However, those fertile soils would not yield their bounty without sweat, toil, and a struggle against a climate so harsh that it drove some settlers to madness. The hearty folk who remained eventually thrived and developed some of the most productive agricultural land in the world. The Red River of the North flows through these bountiful lands and lies at the very heart of the continent. The resultant continental climate sees yearly temperature swings of 130°F or more and severe weather in the form of flooding, drought, blizzards, tornadoes, thunderstorms, and almost incessant high winds. Longer-term climate cycles impose their effects on the area's weather as well, resulting in the droughts of the "dirty thirties" and the floods of the past two decades.

Those who seek to live in the region would do well to learn from the lessons of the past and develop infrastructure and strategies that anticipate these extreme climatic conditions. The Waffle concept was developed in the wake of the most devastating climatic event to hit our valley in historic times, the 1997 flood. Described as "a blinding flash of the obvious" by Energy & Environmental Research Center (EERC) Director Gerald Groenewold, the idea's champion and the person who coined the term "Waffle," the concept uniquely meets three very critical criteria for any practical water management strategy in the region: 1) it has utility for both flooding and drought mitigation, 2) it takes advantage of existing infrastructure and protects both the rural and urban parts of the basin, and 3) it does not threaten the agricultural income that is the region's lifeblood. As residents of the basin who were hard hit by the 1997 flood, the EERC and its partners were strongly motivated to find a solution to flooding that could help keep our basin more secure from future extreme weather events. This report describes the results of that effort and provides a roadmap for those interested in implementation of this and other basinwide water management strategies in the future.

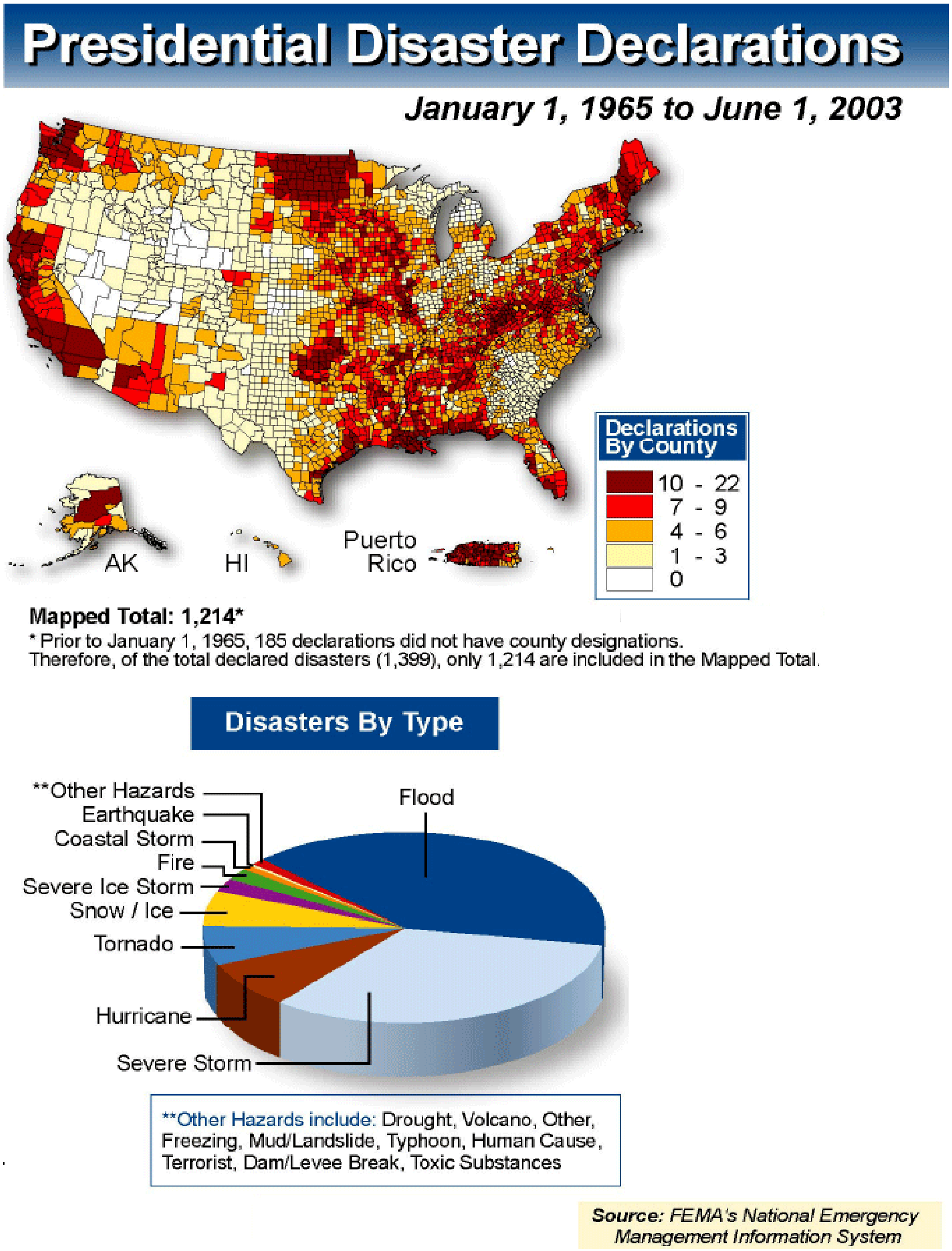
The Red River of the North Basin (RRB) has a long history of extreme climate shifts, from severe droughts to pronounced wet cycles, that result in devastating spring and summer floods. EERC research focused on the reconstruction of paleoclimatic conditions suggests that frequent climatic fluctuations resulting in alternating periods of drought and wet conditions are typical for the northern Great Plains. Although many of us have come to think of the 1930s drought and the 1997 flood as the worst-case scenario, this research also suggests that the recurrence interval of wet and dry conditions averages about 150 years, and the severity and length of extremes exceed those on modern record (Solc et al., 2005). Most of the period of human settlement in the RRB has been characterized by moderate climate conditions, with only a few relatively short shifts to extreme conditions. For example, during the period of rapid population growth from 1862 to 1948, there were few major floods along the Red River (International Joint Commission, 1997).

Assuming that regional climatic conditions will continue to be favorable is a tremendous gamble with devastating consequences. To ensure economic stability, the RRB's communities and residents need to be better prepared to face floods and droughts that are more extreme than those previously experienced during widespread human settlement of the region.

Flooding along the Red River has occurred for thousands of years but did not become a problem until humans built settlements in the floodplain. Now that those settlements have grown into towns and cities, much time and money have been spent trying to keep the floodwater of the Red River from impacting people and communities. This is reflected quite well by the prevalence of presidential disaster declarations in our region from 1965 to 2003, most of which are due to floods (Figure 1). While various structural and nonstructural measures have been investigated and implemented (International Joint Commission, 1997, 2000; Red River Basin Board, 2000; Kingery et al., 1999; and Dyhouse, 1993), the extensive and devastating flooding in 1997 necessitated reexamination of these measures and exploration of innovative concepts to augment traditional approaches. There is no single solution for flooding in this basin, and innovative solutions that address runoff before it becomes a problem are especially crucial to ensure long-term security from flooding for the citizens of the RRB.

To address the need for comprehensive, basinwide flood mitigation measures, the EERC undertook a program to provide an objective evaluation of an innovative, nonstructural flood mitigation concept to provide a means of flood mitigation for cities, towns, and farmsteads. Funding for this project was provided by the Natural Resources Conservation Service (NRCS) in 2002. The main goal of the project was to determine the feasibility of utilizing a basinwide system for temporary storage of floodwater in the RRB to help mitigate large, springtime floods such as occurred during 1997. The flood mitigation effect, referred to as the Waffle concept, would be accomplished utilizing existing "depressions" within the basin, primarily ditches and low-relief fields bounded by existing roads, for temporary storage of springtime runoff. The storage areas, roads, and drainage structures would act as a network of channels and control structures to temporarily store water until the Red River flood crest passes. Although by no means a natural system, the Waffle would work with existing infrastructure to mimic a natural system by slowing the progress of water to the Red River and its tributaries. The Waffle concept addresses excess runoff before it enters the streams and rivers of the RRB and becomes a problem, thereby lessening the volume of water needed to be retained by dikes or redirected by downstream diversions.

In addition to helping reduce costs associated with flooding, the Waffle project may offer benefits to farmers in both wet and dry years. On average, nearly a third of the water that flows down the Red River each year comes during April (Figure 2). In most years, the problem is not that there is too much water, but that water is not available when it is needed most. For example, rather than allowing water from snowmelt to run off, it could be stored to help farmers increase soil moisture. Water captured in the Waffle during the spring could also be used to recharge aquifers that are depleted by droughts and for irrigation and municipal use.



Source: FEMA's National Emergency Management Information System

Figure 1. Map of county-based presidential disaster declarations throughout the United States from 1965 to 2003.

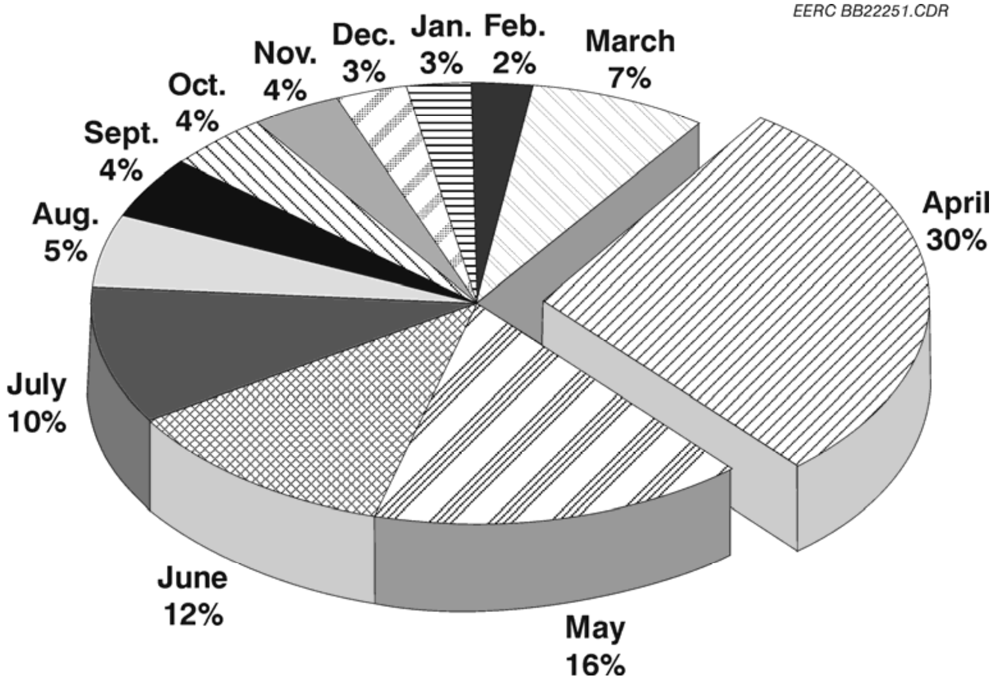


Figure 2. Monthly distribution of annual stream flow for Red River (based on U.S. Geological Survey [USGS] flow data).

The results and recommendations developed through this evaluation are being provided to policy makers in the basin. Implementation will require buy-in of federal, state, and local water management agencies and coordination by state and regional entities. Because it has potential benefits to both urban and rural residents, the Waffle plan represents a chance to cooperate on water management throughout the basin and, for the first time since European settlement, provide true long-term security from flooding.

1.2 Background

The Red River originates at the confluence of the Bois de Sioux and Otter Tail Rivers, forms the boundary between North Dakota and Minnesota, and enters Canada at Emerson, Manitoba, where it continues northward to Lake Winnipeg, Manitoba (Figure 3). It meanders approximately 548 mi (883 km) through the flat and fertile valley of former glacial Lake Agassiz, forming the 45,000-mi^2 (116,500-km^2) RRB. Both the river channel and the basin are intersected by the international border between the United States and Canada, with approximately 75% of the RRB located in the United States. Twenty-seven subwatersheds contribute to Red River flows in the U.S. portion of the RRB (Figure 4). These subwatersheds, which are defined by USGS 8-digit hydrologic unit codes (HUCs), have an average drainage area of 1335 square miles, with a range of 482 mi^2 to 2380 mi^2 (Table 1).

Several major urban areas are located on the banks of the Red River, including Wahpeton–Breckenridge with a combined population of 12,000, Fargo–Moorhead at 100,000, Grand Forks–East Grand Forks at 60,000, Winnipeg at 670,000, and Selkirk at 9800 (International Joint

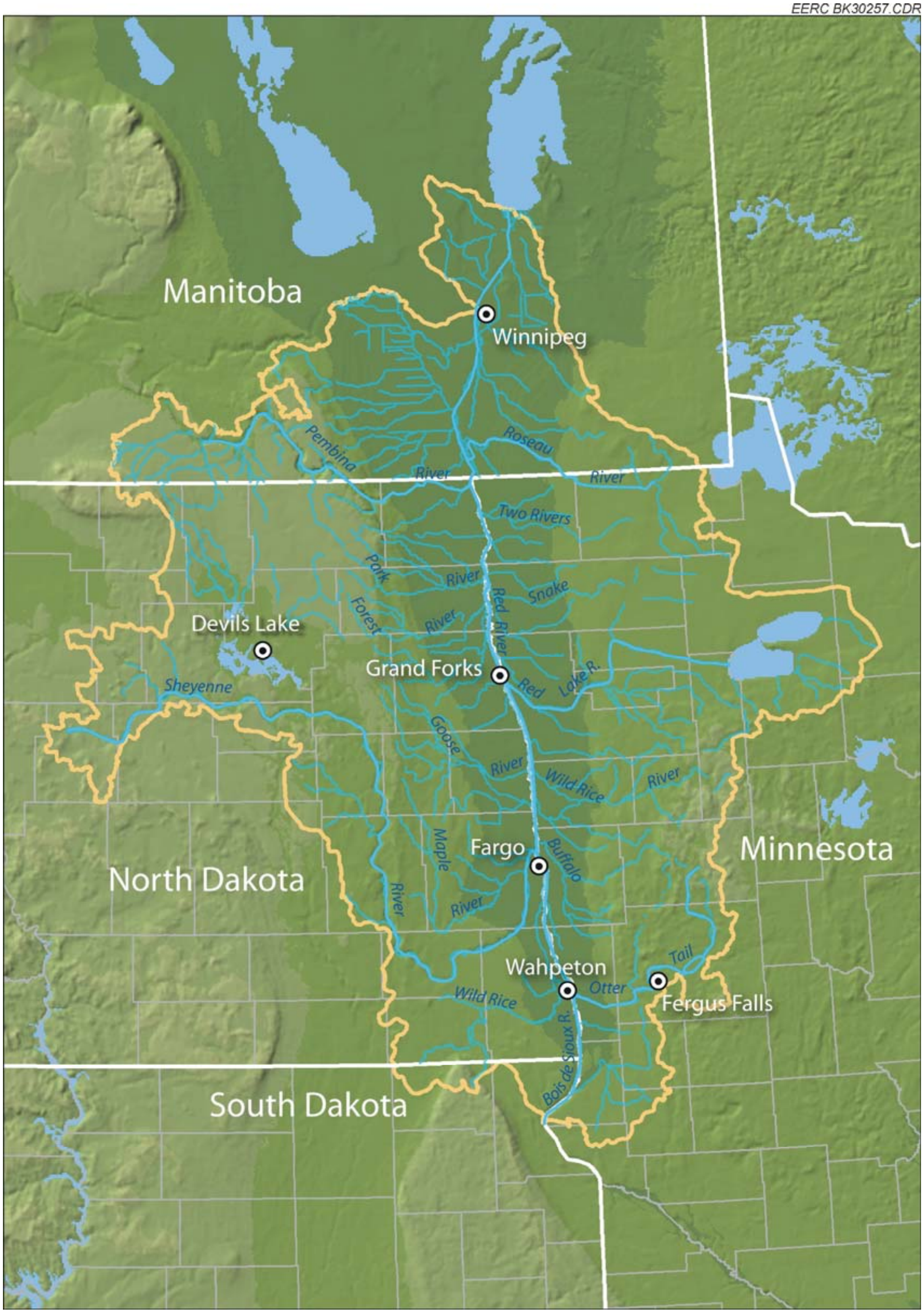


Figure 3. Red River of the North Basin.

Figure 4. Major subwatersheds of the RRB.

Table 1. Major Watersheds Comprising the RRB, Corresponding HUCs, and Drainage Area

No.	HUC	Name	Drainage Area, mi^2	Administration Boundary
1	09020101	Bois de Sioux	1140	Minnesota, North Dakota
2	09020102	Mustinka	825	Minnesota
3	09020103	Otter Tail	1980	Minnesota
4	09020104	Upper Red	594	Minnesota, North Dakota
5	09020105	Western Wild Rice	2380	North Dakota
6	09020106	Buffalo	1150	Minnesota
7	09020107	Elm–Marsh	1150	Minnesota, North Dakota
8	09020108	Eastern Wild Rice	1670	Minnesota
9	09020109	Goose	1280	North Dakota
10	09020202	Upper Sheyenne	1940	North Dakota
11	09020203	Middle Sheyenne	2070	North Dakota
12	09020204	Lower Sheyenne	1640	North Dakota
13	09020205	Maple	1620	North Dakota
14	09020301	Sandhill–Wilson	1130	Minnesota, North Dakota
15	09020302	Red Lakes	2040	Minnesota
16	09020303	Red Lake	1450	Minnesota
17	09020304	Thief	994	Minnesota
18	09020305	Clearwater	1350	Minnesota
19	09020306	Grand Marais–Red	482	Minnesota, North Dakota
20	09020307	Turtle	714	North Dakota
21	09020308	Forest	875	North Dakota
22	09020309	Snake	953	Minnesota
23	09020310	Park	1080	North Dakota
24	09020311	Lower Red	1320	Minnesota, North Dakota
25	09020312	Two Rivers	958	Minnesota
26	09020313	Pembina	2020	North Dakota
27	09020314	Roseau	1230	Minnesota

Commission, 2000). Over 66% of the RRB is conducive to agriculture because of the fertile, black, and fine-grained soils (Stoner et al., 1993). As such, the region's economy is dominated by agriculture and agriculture-related activities.

The RRB is subject to frequent damaging inundation from both minor and major flood events. Since official record keeping began in 1882, major floods affecting large areas of the basin have occurred once in about every 4 to 6 years, with a truly devastating flood about every decade (LeFever et al., 1999; International Joint Commission, 1997). Major historical floods occurred in 1826, 1852, 1882, 1897, 1950, 1952, 1966, 1969, 1978, 1979, 1989, 1996, 1997, 2001, and 2006. It is interesting to note that in Grand Forks, four of the top 10 largest floods have occurred in the past 10 years, namely 1996, 1997, 2001, and 2006. In Fargo, the 1997, 2001, and 2006 floods were among the top five largest floods since 1882. Historical accounts and tree ring data suggest that the spring flood of 1826 was the most severe flood during the last 357 years (International Joint Commission, 1997; Brooks et al., 2003). While all of the other floods caused severe damage, the 1997 flood is the worst in the official record and caused an estimated $5 billion in damages throughout the RRB (International Joint Commission, 2000).

Bluemle (1997) attributed flooding in the RRB to a combination of both relatively stable and variable factors. The stable factors include 1) the Red River's northerly flow, which creates problems with ice jams as the headwaters thaw and begin flowing before downstream reaches; 2) the more rapid transport of runoff from the landscape to major waterways as a result of urbanization and over 28,000 mi (45,060 km) of anthropogenic drainage ditches (Red River Basin Board, 2000); 3) the low gradient and low-flow velocity of the river; and 4) the occurrence of structural features such as bridges, culverts, and dikes. In addition to these stable factors, five variable factors may combine to create a major flood: 1) a wet fall; 2) a cold winter; 3) heavy winter snow accumulation; 4) a late, cool, wet spring followed by rapid warming; and 5) widespread, heavy, warm rainfall during the thawing period. Bluemle also speculated that when compared with the stable factors, the variable factors have a higher correlation to major floods in the RRB.

LeFever et al. (1999) examined the contributions of the aforementioned factors to major historical floods and determined that all of the variables discussed by Bluemle were factors in the 1997 flood. Probably the most notable factor was record or near-record snowfall throughout the RRB, which, in most areas, was two to three times greater than average (International Joint Commission, 1997). Snowfall was approximately 98 inches in Grand Forks and 117 inches in Fargo, compared to long-term snowfall averages ranging between 41 and 39 inches, respectively (Macek, 1997; International Joint Commission, 1997; Zandlo et al., 1997). Snowmelt in the RRB began in the southern part of the region beginning on about March 21 and migrated northward until April 4, at which point an early spring blizzard and colder temperatures moved into the region (Todhunter, 2001). The April 5−6 spring blizzard exacerbated the flooding problem by depositing two or more inches of precipitation (in the form of rain or snow) in many areas of the RRB (Zandlo et al., 1997). For example, Crookston, Minnesota, received the equivalent of 3.6 inches of water (Macek, 1997).

Rapid late-season warming was also a major factor in the 1997 flood (International Joint Commission, 1997). Temperatures began warming again about 5 days after the blizzard, with significantly warmer temperatures hitting the entire region by April 16 (Todhunter, 2001). As an unusually rapid thaw (Todhunter, 2001) occurred throughout the region, flooding along the Red River and its tributaries progressed northward. Red River peak flood stages occurred in Wahpeton, North Dakota, on April 6; Fargo, North Dakota, on April 18; and Grand Forks, North Dakota, on April 22 (Macek, 1997). The flood caused the evacuation of nearly 75,000 residents in the Red River Valley (Todhunter, 2001) and an estimated $5 billion in damage (International Joint Commission, 2000).

Although many RRB residents have come to view the 1997 flood as the worst-case scenario, past history has demonstrated that this is not the case. Based on historical accounts, the flood of 1826 was estimated to have flows 40% larger than 1997 flows in Winnipeg (St. George and Rannie, 2003) and 26% larger than 1997 flows in Grand Forks (U.S. Army Corps of Engineers and Federal Emergency Management Agency, 2003). A flood of 1826 magnitude would likely cause widespread and devastating damage throughout the region since no cities, towns, or rural areas are protected by structural measures for floods of this magnitude. Unfortunately, the residents of Grand Forks learned the hard way what can happen when a city relies too heavily on one means of flood protection. The extensive flooding in 1997 raised awareness of the flooding problem in the RRB and underscored the need for the reexamination of the efficacy of existing flood mitigation measures. As stated by the International Joint Commission (IJC) in a 2000 report, “besides creative structural measures, innovative concepts of nonstructural measures should be explored to augment the design capacities of structural measures planned to protect against future floods similar in scope to, or greater than, the 1997 flood” (International Joint Commission, 2000).

Commonly proposed, and often debated, basinwide water retention approaches include structural measures, such as additional new main stem dams on the tributaries of the Red River; dry dams; constructed wetlands; off-channel storage impoundments; and nonstructural options such as the reestablishment of drained wetlands; establishment of greenways; increased implementation of alternative agricultural practices (Hollevoet, 1999); riparian restoration; reestablishment of meanders in channelized streams; and short-term basinwide microstorage using a small percentage of land bounded by section line roads (the Waffle concept). Although these various approaches are dramatically different both conceptually and with respect to implementation, all reflect a growing consensus that meaningful flood protection will require a combination of practices coupled with the development of strategic basinwide planning and partnerships.

Given the severe flooding that has impacted the region in recent years, an augment to traditional structural systems is needed to ensure long-term security from flooding for the citizens of the RRB. Although various flood mitigation measures have been evaluated and implemented, a comprehensive evaluation of the viability of a basinwide approach for the reduction of main stem flooding in the Red River had never been accomplished. This was the goal of the EERC’s Waffle project. This concept is consistent with the international trend toward nonstructural basinwide approaches to flood control and could become a model for flood control strategies in the new millennium.

1.3 The Waffle Concept

As previously mentioned, the Waffle approach entails utilizing the infrastructure of the RRB for temporary storage of local springtime runoff. Figure 5 illustrates the Waffle concept, whereby the system of existing roads (state, county, and township) would be utilized to create temporary storage areas in fields bounded by roads that are higher than the land they surround. Most of the roads surrounding agricultural land contain at least one culvert to help drain water as well as a system of ditches that are located adjacent to the roads. The Waffle concept proposes to utilize and modify the existing system of culverts and ditches to provide the mechanism for water retention and controlled drainage. Local runoff would be retained on individual storage sections by outfitting at least one of the existing culverts with a vertical riser, or stand pipe, followed by a canal gate to allow for controlled release of the water following storage (Figure 6). Any remaining culverts on the storage section would be outfitted with canal gates that would be closed during the storage period. Because the top of the stand pipe is open, the storage volume for a given section is governed by the elevation of the top of the stand pipe. This elevation would have to be predetermined to 1) ensure that there is some degree of freeboard between the stored water surface elevation (at full capacity) and the elevation of the lowest point along the surrounding roads, 2) to prevent water from backing up onto the land of someone that is not

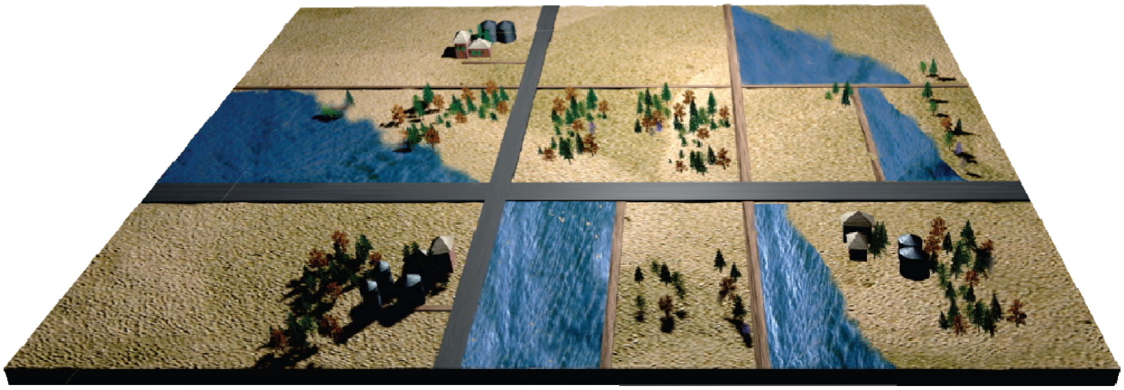


Figure 5. Illustration of water storage using Waffle concept.

Figure 6. Water retention in Waffle storage section using gated culvert and overflow standpipe.

participating in Waffle storage, and 3) to ensure that drainage in upstream ditches is not backed up as a result of the temporary storage. In many cases, depending on the minimum road elevation, only a portion of the storage area would be flooded. Once the major flood crest passed, the stand pipe canal gate would be partially opened, and the stored water would be slowly released to minimize erosion and flooding of downstream ditches. The release of water from various storage areas would be coordinated to reduce flood crests downstream. Based on field trials of the Waffle concept, average storage sections will likely require 24 to 36 hours to drain completely. Once a given storage section is drained, all of the canal gates would be opened to full capacity to allow for unrestricted flow of runoff from storms or precipitation that occurs during the growing season.

Although the Waffle concept is compatible with the integrated watershed-based approach recommended by the National Research Council (1999), it has been widely discussed and debated because the feasibility of establishing such a large-scale project raises many important questions and challenges. Most of the key issues and concerns raised about the Waffle concept are included and/or addressed in Section 3 of this report; however, some of the concerns raised were based on misconceptions of the Waffle concept. Therefore, it is constructive to provide a few additional details of the concept at this point to clear up some key misconceptions. The following are the assumptions used by the EERC in evaluation of the Waffle concept:

- The EERC evaluated the Waffle concept with the assumption that participation would be voluntary (meaning no one would be forced to store water) and that landowners/ producers would be reimbursed for any damages caused by their participation.

- The EERC assumed that water would not be stored during the summer when crops are present. Although there have been several major summer flood events in recent years (i.e., 2001, 2002), the Waffle approach was only proposed as a means of mitigating large springtime floods.

- Waffle storage would not preclude planting of agricultural crops. Delays in planting would likely be minimal, and landowners/producers would be reimbursed for any estimated reduction in crop yields as a result of delayed planting. In addition, the additional soil moisture could provide a benefit to crops during dry years.

- Assuming the Waffle concept is used only to mitigate large springtime floods, water would only be stored in Waffle sections if conditions indicated that this type of flood was imminent.

- Water stored in Waffle sections would originate either from precipitation (snowmelt) from each storage parcel or from water flowing into the section from upstream culverts. Water would not be diverted from streams or tributaries to fill a storage section.

- Although actual storage times may vary upon implementation, it was assumed that water would be stored for an average of approximately 14 days before release.

- This evaluation assumed that existing roads would be utilized to store water and that no roads would be raised.

Obviously, these assumptions could be altered as seen fit by policy makers, watershed managers, and landowners/producers if this practice were implemented.

The concept of temporarily storing water in low areas has been previously investigated in North Dakota through the Create-A-Wetland Project (BlueStem Incorporated, 1996; Spoor, 1992; Schroeder and Goldman, 1990). This project, conducted through the North Dakota Wetlands Trust, demonstrated the effects of controlled preplant flooding on spring grains for agricultural land located in Bottineau County. The study, which was initiated in 1989, entailed the temporary impoundment of surface water runoff in drained wetlands on fields that were scheduled for small grain production. To store the water until the scheduled release date of April 15, gated culverts were installed in the drainage ditches of the sites. Water storage occurred on about 30 sections in Bottineau County during 1989, 1992, 1993, and 1994. Because of drought conditions from 1989 to 1993, there was little to no runoff and, therefore, limited storage. The landowners participating in the study were given a one-time payment for each culvert/control gate installed and an annual payment based on the number of flooded acres for the first 3 years of participation. Differences in crop yields were monitored on several sites during 1992. The results showed that grain yields increased anywhere from 29% to 141%, with an average increase of approximately 74% where water was temporarily stored. In addition, use of the wetlands by migratory waterfowl was documented. An evaluation of the flood mitigation benefits of the temporary storage areas was not conducted.

A small-scale evaluation of Waffle-type storage was conducted by Kingery et al. (1999) in the Pembina River Basin. This study investigated the utility of springtime flood control by temporary surface water storage in fields, pastures, ditches, drains, and other depressions. The study used ArcView 3.0 geographic information system (GIS) software to quantitatively evaluate potential surface water storage in the Mowbray Creek Watershed, a subwatershed of the Pembina River Basin. Using GIS and 1:24,000 USGS topographic maps, the authors concluded that approximately 9000 ± 1800 acre-ft of storage could be achieved throughout the subwatershed, more than enough to reduce the 1997 flood to less than a 10-year event on Mowbray Creek. The study concluded that the reduction of peak flows was possible with relatively few changes in infrastructure.

The results of the above studies were encouraging; however, an evaluation of small-scale, temporary storage throughout the RRB was needed to objectively determine whether or not the concept could provide flood mitigation benefits throughout the entire region. Thus, beginning in the Spring of 2002, the EERC embarked upon a 4-year investigation to determine the feasibility of utilizing the Waffle approach for basinwide mitigation of large, springtime floods. The evaluation of the Waffle concept proceeded with a series of tasks that were grouped based on whether they pertained to the technical, social, or economic feasibility of the concept. The key tasks of the technical evaluation included the following:

- Compilation of new and existing data needed to evaluate the Waffle concept.

- Estimation of maximum storage needs using existing models.

- Identification of potential Waffle storage locations and volumes throughout the RRB.

- Development of models needed to evaluate the Waffle concept on a subwatershed basis as well as basinwide.

- Demonstration-scale evaluation of the Waffle concept at field trial sites to assess the effectiveness of the mitigation effort, to evaluate potential impacts to crop production and road stability, and to refine and improve future implementation procedures.

Evaluation of the social feasibility of the Waffle concept was conducted through the following:

- Communication of the Waffle concept and progress through presentations, a Waffle Web site, newsletters, reports, TV and radio broadcasts, and newspaper articles

- Compilation of public concerns and issues through extensive outreach and meetings with relevant stakeholder groups

- Development and evaluation of landowner/producer surveys.

The economic evaluation of the Waffle concept entailed a first assessment of the cost-effectiveness of the Waffle through comparison of potential mitigated flood damage (benefit) estimates versus implementation and maintenance costs. This evaluation was conducted by economists at North Dakota State University (NDSU).

Throughout the duration of the study, project activities were communicated to two advisory boards, an Agency Advisory Board (AAB) and a Citizens' Advisory Board (CAB). A list of advisory board members can be found at the beginning of this document. These boards helped to advise the EERC project team regarding Waffle-related activities, and they provided input regarding potential technical, economic, and social concerns. The members of these boards were asked to provide objective input and were not necessarily supportive of the Waffle concept. The primary functions of both boards were:

- To provide advice and expertise to enhance the Waffle project outcomes.

- To make recommendations regarding new and/or existing directives to be undertaken by the Waffle team.

- To serve as a working group by providing recommendations and reviewing ideas and strategies related to flood mitigation and basinwide water storage.

The AAB comprised representatives from various federal, state, and local entities (with expertise in natural resource management, water management, hydrology, biology, ecology, and computer modeling). The primary objective of the AAB was to advise and counsel EERC personnel regarding the technical activities of the Waffle project as they relate to the evaluation of temporary basinwide water storage. The kickoff meeting for the AAB was held in October 2002, and eleven meetings were held over the course of the study. Many of the suggestions provided by the board members were within the planned scope of work of the project and were accommodated in project activities.

The CAB comprised citizens, farmers, and/or landowners of the RRB with experience and/or interest in farming, flooding, droughts, water storage, and/or drainage. The primary function of the CAB was to advise and counsel EERC personnel regarding landowner concerns and opinions about temporary water storage, drainage, flooding, and drought. The CAB also provided input and suggestions regarding the EERC's outreach strategy and how to best communicate the project concept and gain input from key stakeholders. The first meeting of the CAB was held in January 2003, and ten meetings were held throughout the course of the study. The advice and recommendations contributed by the CAB are discussed further in Section 3.0 of this report.

Originally, the Waffle work plan focused largely on evaluating the technical feasibility of the concept, with the idea that if Waffle storage could not significantly reduce the flows of the Red River and its tributaries, then evaluating the economic and social feasibility of the concept was pointless. However, through advice and input obtained by the advisory boards, the general public, and various local and regional water management groups, it became evident that a greater focus then was originally planned was needed regarding the social and economic feasibility of the concept.

2.0 TECHNICAL APPROACH AND RESULTS

The Waffle project was designed to test the technical, societal, and economic efficacy of the concept as a flood mitigation tool. The ultimate goal was to provide decision makers and stakeholders with the information they would need to effectively implement the concept if they chose to do so. In order to conduct a feasibility assessment of the technical components of the Waffle concept, the following key questions had to be addressed:

- How much water would need to be stored to prevent the Red River from reaching major flood stage during a 1997-size flood?
- How much water can be stored in a Waffle-type manner throughout the RRB?
- Where are the most likely locations for water storage?
- If Waffle storage were implemented, how much would peak flows be reduced from each of the major Red River tributaries?
- How much would flow reductions within the RRB tributaries reduce peak flood stage at key points along the Red River during a 1997-type flood?
- How would the water physically be stored with the Waffle approach?
- Would the water quality of stored runoff be affected by temporary storage?
- What would the localized impacts of Waffle storage be?

- How much could flows be reduced in ditches and/or waterways adjacent to storage sites?

- Would road stability be impacted as a result of Waffle storage?

One of the key limitations in addressing the above questions was the lack of high-resolution elevation data for the RRB and a general lack of infrastructural data, such as road elevations and culvert locations and specifications. The following section describes the approach taken to address the above technical questions and the results of this research.

2.1 Data Survey and Database Construction

The goal of the data survey was to identify the suitability, reliability, and accuracy of existing data and information needed to evaluate the feasibility of the Waffle concept. As such, a major effort in the first year of this study was spent determining what data, studies, and models already existed for the RRB. This not only required searches of conventional data sources, such as USGS and NRCS, but also entailed surveying less conventional data sources, such as watershed districts, water resource boards, county engineers, and local Department of Transportation (DOT) offices. If the data sets were relevant, they were collected for use in the Waffle study.

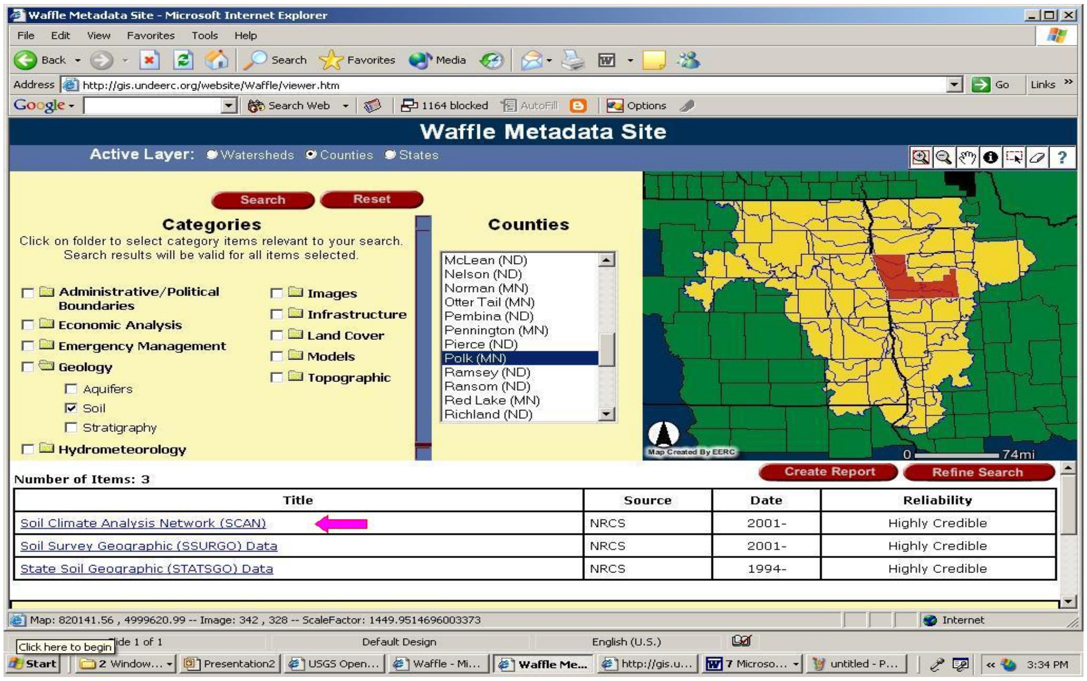
The primary data types of interest for this project included the following:

- Models (i.e., hydrologic and hydraulic computer models)
- Infrastructure (i.e., culvert and bridge locations and elevations, road elevations)
- Topography (i.e., high- and low-resolution digital elevation data)
- Geology (i.e., soil information)
- Hydrometeorology (i.e., weather station data)
- Imagery (i.e., aerial photographs, satellite images)

The specific data sets ultimately used in the evaluation of the Waffle concept are discussed in various sections of this report. Details describing the data surveyed and collected through the Waffle study are described in Appendix A.

After the data survey was completed, the EERC determined that the information compiled would also be of interest to other entities involved in natural resource studies in the RRB. An interactive, Web-based database was developed to contain information on the type, location, and reliability of data available for the RRB (Figure 7). The database is available to the public through the Waffle Web site (www.undeerc.org/Waffle). Pertinent information regarding the data ownership, location, reliability, and documentation is provided and, if available, the data creation date, scale, and format.

Users of the database can conduct data queries based on political boundaries, such as states or counties, or based on natural boundaries, like watersheds. In addition, queries can be conducted based on a specific data type, such as soil data, or topography. Alternatively, a user can search by title or publication year and be prompted by utilizing a series of drop-down



Waffle Metadata Site

Active Layer: ○ Watersheds ● Counties ○ States

Categories

Click on folder to select category items relevant to your search. Search results will be valid for all items selected.

- ☐ Administrative/Political Boundaries
- ☐ Economic Analysis
- ☐ Emergency Management
- ☐ Geology
  - ☐ Aquifers
  - ☑ Soil
  - ☐ Stratigraphy
- ☐ Hydrometeorology
- ☐ Images
- ☐ Infrastructure
- ☐ Land Cover
- ☐ Models
- ☐ Topographic

Counties

McLean (ND)
Nelson (ND)
Norman (MN)
Otter Tail (MN)
Pembina (ND)
Pennington (MN)
Pierce (ND)
Polk (MN)
Ramsey (ND)
Ransom (ND)
Red Lake (MN)
Richland (ND)

Number of Items: 3

Title	Source	Date	Reliability
Soil Climate Analysis Network (SCAN)	NRCS	2001-	Highly Credible
Soil Survey Geographic (SSURGO) Data	NRCS	2001-	Highly Credible
State Soil Geographic (STATSGO) Data	NRCS	1994-	Highly Credible

Map: 820141.56 , 4999620.99 -- Image: 342 , 328 -- ScaleFactor: 1449.9514696003373

Figure 7. Screen capture of Waffle metadata site showing a query conducted for soil data in Polk County.

selections. When a data set or resource of interest is found, additional detail is provided, including instructions on how to obtain the resource. Some of the resources are maintained online for immediate transfer, while others need to be ordered.

A similar database was also constructed for the flood-related literature collected through this project. This interactive database is available to the public on the Waffle Web site and contains over 400 references that were compiled using Reference Manager®. Users can search the contents of this database by author, keyword(s), and title. Query results include full reference citations and, whenever possible, publication abstracts. If the abstract of a publication was not available, an executive summary or introduction was cited as long as special copyright permission was granted by the publishers.

2.2 Preliminary Estimation of Maximum Storage Needs

At the beginning of the Waffle study, preliminary research was conducted to estimate the storage volumes needed throughout the basin to have prevented the Red River from reaching major flood stage at several key points during the 1997 flood. Although reducing 1997 flood levels to major flood stage exceeds the stage reductions necessary to mitigate large-scale damage, the estimates were conducted to gain a sense of the upper limit of storage volumes necessary to achieve a major reduction in river stage. Further, the 1997 flood is the flood of record and represents a well-recognized benchmark for measuring the potential effectiveness of the Waffle concept.

To conduct this effort, a simplistic model, shown in Figure 8, was developed by integrating existing hydrologic and hydraulic models with new mathematical algorithms. The existing Hydrologic Engineering Center (HEC)–2 and HEC–River Analysis System (RAS) models, developed by the U.S. Army Corps of Engineers (USACE) (www.mvp-wc.usace.army.mil/org/RRN), were calibrated using the 1997 high-water-mark data provided by USACE and the Federal Emergency Management Agency (FEMA). Assuming major flood stage was the targeted protection elevation (TPEL) for key locations along the Red River (USACE, 2001), these models were used to determine the maximum allowable discharge values (Q_{max}). By shaving the peaks with Q_{max}, the USGS daily stream flow hydrographs observed in 1997 (http://waterdata.usgs.gov/nwis/discharge) were manipulated to compute the water volume that needs to be regulated upstream of these targeted protection locations W_{lpR}. Flow hydrographs from ungauged drainage areas (i.e., the areas not monitored by USGS gauging stations) were estimated using an existing HEC–1 model coupled with subjective engineering judgment (Houston Engineering Inc., 1999). A storage–release algorithm was developed and utilized to allot the computed water volumes to the subwatersheds upstream of the targeted protection locations.

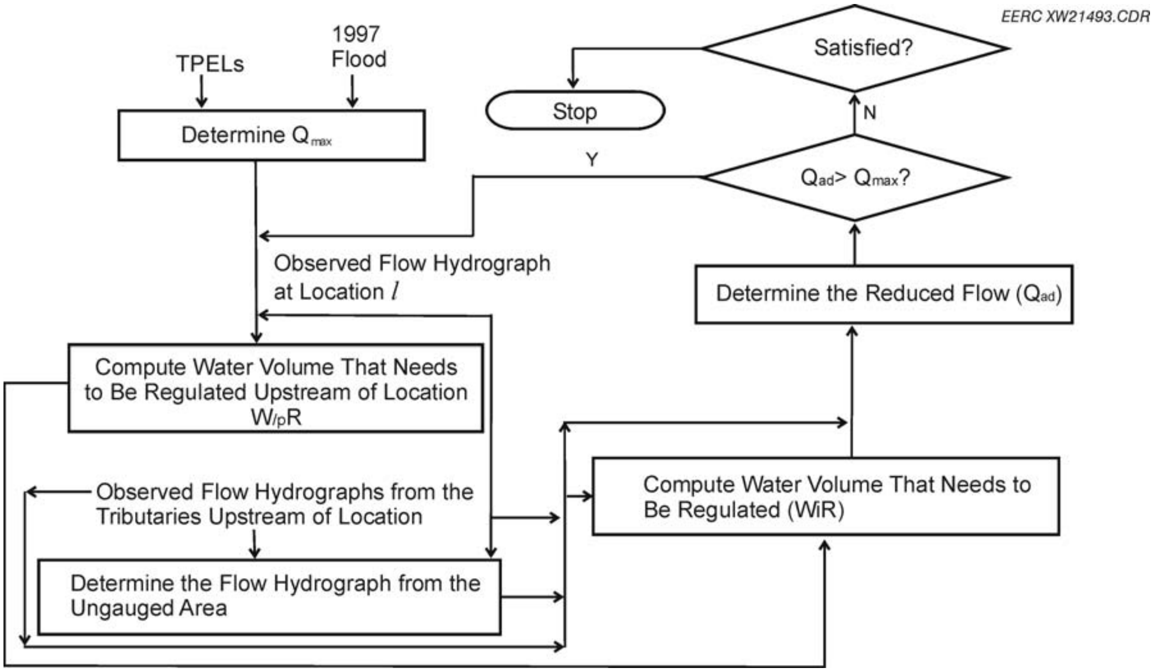


Figure 8. Simplified model to study reducing 1997-type flooding of the Red River.

The storage algorithm assumes that the subwatersheds that contributed more runoff will regulate more water. Thus the water to be regulated, W_{ir}, by subwatershed i upstream of the targeted location, *l*, may be estimated by Equation 1.

$$W_{iR} = \frac{W_{ic}}{W_{lp}} \times W_{lpR} \qquad \text{[Eq. 1]}$$

Where: W_{ic} = Observed runoff volume from subwatershed i
W_{lp} = Observed total runoff volume at location *l*
W_{lpR} = Computed water volume that needs to be regulated upstream of location *l*

On the other hand, the release algorithm, is based upon shaving the peak at the latest possible high-flow period but releasing the water at the earliest possible low-flow period. Thus the reduced flow hydrograph, Q_{ad}, at location *l* and the outlet of subwatershed i may be estimated by Equation 2.

$$Q_{ad} = \begin{cases} Q_{ob}\left(1 - \dfrac{W_R}{W_{ob}}\right) & \text{Storage period} \\ \dfrac{1}{} & \\ Q_{ob} + \dfrac{Q_{ob}}{W_{ob}} W_R & \text{Release period} \end{cases} \qquad \text{[Eq. 2]}$$

Where:
Q_{ob} = Observed daily stream flow
W_{ob} = Observed runoff volume
W_R = Computed water volume that needs to be regulated, equal to W_{lpR} or W_{iR}

The results simulated by this simplistic model are given in Table 2. The output data were compiled for the seven drainage subbasins that have outlets at USGS gauging stations along the main stem (Wahpeton, Hickson, Fargo, Halstad, Grand Forks, Drayton, and Emerson). Under preexisting conditions (prior to the Grand Forks–East Grand Forks flood protection project) to reduce the 1997 flood crests below major flood stage at various locations along the Red River, approximately 1,317,629 acre-ft of water would need to be regulated upstream of Drayton, including 180,000 acre-ft upstream of Wahpeton–Breckenridge, 126,772 acre-ft between Wahpeton–Breckenridge and Fargo–Moorhead, 166,374 acre-ft between Fargo–Moorhead and Halstad, 596,854 acre-ft between Halstad and Grand Forks–East Grand Forks, and 247,629 acre-ft between Grand Forks–East Grand Forks and Drayton. With this volume of water regulated upstream of Drayton, the water surface elevation (WSEL) at Emerson would be below its major flood stage. The volume of water regulated upstream of Drayton was allotted to the subwatersheds using the storage release algorithm. Water depths, averaged by the contributing areas of the subwatersheds, vary from 0.2 to 2.6 inches per subwatershed (see Table 2), with the maximum depth occurring in the Elm–Marsh subwatershed upstream of the USGS Shelly gauging station.

A comparable simulation was also analyzed with the Grand Forks–East Grand Forks levee project completed (Table 2, postproject conditions). Under the postproject conditions, Grand Forks–East Grand Forks would not need to regulate water upstream. However, the same volume of water would have to be regulated upstream of Wahpeton–Breckenridge, Fargo–Moorhead, and Halstad to protect these locations in their major flood stages. By regulating only the excess runoff from the subwatersheds between Grand Forks–East Grand Forks and Drayton, there would not be enough storage to prevent Drayton from reaching major flood stage. Additionally, approximately 104,131 acre-ft of water would have to be regulated between Drayton and Emerson to protect Emerson to its major flood stage. Under postproject conditions, the average

Table 2. Flood Reduction Analysis Along the Main Stem of the Red River for the 1997 Flood. The following table lists the approximate volumes of water that would need to be regulated upstream of key locations (highlighted in gray) along the Red River to keep them from reaching major flood stage. The key locations evaluated include Wahpeton, Hickson, Fargo, Halstad, Grand Forks, Drayton, and Emerson. The rows beneath each major location contain information on those areas that contribute to the flows at the respective location, and include the upstream main stem station, the stations controlling flows from the major tributaries, and the ungauged area. The data listed in the columns includes the elevation of the respective gauging station; the contributing and noncontributing drainage area upstream of the gauging station; the peak discharge during the 1997 flood; the high-water mark during the 1997 flood; and the volume of water generated upstream of a particular gauging station or contributed by ungauged areas from March 1 to May 31, 1997. The following data are also provided, but, in each case, values are given for the conditions prior to and after the Grand Forks–East Grand Forks flood protection project: the volume of water that would need to be regulated upstream of the respective gauging station or within the ungauged area to prevent the key Red River evaluation locations from reaching major flood stage; the average depth of water that would need to be regulated throughout the contributing area; the predicted reduced peak discharge (after water regulation); and the revised high-water mark (after water regulation).

		Drainage Area[a], mi^2		Peak Discharge[b]			Volume from	Water That Needs to Be Regulated Upstream, ac-ft		Average Regulated Water Depth Throughout the Contributing Area, in.		Reduced Peak Discharge, cfs		Revised High Water Mark, ft	
Control Location	Elevation, ft	Contributing	Non-contributing	Peak, cfs	Date, mo/day	High Water Mark, ft	March 1 to May 31 [c], ac-ft	Preexisting Condition	Postproject in GF and EGF	Preexisting Condition	Postproject in GF and EGF	Preexisting Condition	Postproject in GF and EGF	Preexisting Condition	Postproject in GF and EGF
Wahpeton (05051500)	942.97	2425	1585	12,700	4/15	962.39	782,257	180,000	180,000	1.4	1.4	6100	6100	958.97	958.97
Doran (05051300)		1880		11,500	4/16		490,107	112,775	112,775	1.1	1.1				
Fergus Falls (05046000)	1,029.65	1740		1480	4/16		191,177	43,990	43,990	0.5	0.5				
Ungauged Area		390					100,973	23,234	23,234	1.1	1.1				
Hickson (05051522)	877.06	2715	1585	8920	4/1	914.66	883,237	186,229	186,229	1.3	1.3				
Wahpeton (05051500)	942.97	2425	1585	12,700	4/15	962.39	782,257	180,000	180,000	1.4	1.4				
Ungauged Area		290					100,980	6229	6229	0.4	0.4				
Fargo (05054000)	861.80	4625	2175	25,800	4/19	901.52	1,454,940	306,772	306,772	1.2	1.2	20,000	20,000	893.75	893.75
Hickson (05051522)	877.06	2715	1585	8920	4/1	914.66	883,237	186,229	186,229	1.3	1.3				
Abercrombie (05053000)	907.94	1490	590	9450	4/16	935.24	374,132	78,885	78,885	1.0	1.0				
Ungauged Area		420					197,571	41,658	41,658	1.9	1.9				
Halstad (05064500)	826.65	15,205	6595	69,900	4/19	867.39	3,364,385	473,146	473,146	0.6	0.6	55,000	55,000	865.50	865.50
Fargo (05054000)	861.80	4625	2175	25,800	4/19	901.52	1,454,940	306,772	306,772	1.2	1.2				
West Fargo Diversion (05059480)	876.78	0		4800	4/19		377,077	32,856	32,856						
West Fargo (05059500)	877.19	3090	5780	4800	4/19	899.98	415,259	36,182	36,182	0.2	0.2				
Enderlin (05059700)	1,056.72	796	47	3890	4/18	1070.82	151,495	13,200	13,200	0.3	0.3				
Amenia (05060500)	943.00	116		1450	4/16		36,117	3,147	3147	0.5	0.5				
Dilworth (05062000)	878.31	975		8370	4/6	905.41	232,880	20,291	20,291	0.4	0.4				
Hendrum (05064000)	836.75	1560		10,300	4/18		383,061	33,377	33,377	0.4	0.4				
Ungauged Area		2636					313,556	27,321	27,321	0.2	0.2				
Grand Forks (05082500)	779.00	21,445	8655	127,000	4/18	833.35	5,016,820	1,070,000	473,146	0.9	0.4	110,000	127,000	830.88	833.35

[a] Data for the main stem from USACE (Table 2 included in Regional Red River Flood Assessment Report, Wahpeton, North Dakota–Breckenridge, Minnesota, to Emerson, Manitoba, January 2003); some values are from USGS.

[b] From USGS. The values are the maximum discharges presented in the daily stream flow data.

[c] Computed based on the flow hydrographs from USGS.

Continued . . .

Table 2. Flood Reduction Analysis Along the Main Stem of the Red River for the 1997 Flood (continued)

		Drainage Area[a], mi^2		Peak Discharge[b]				Water That Needs to Be Regulated Upstream, ac-ft		Average Regulated Water Depth Throughout the Contributing Area, in.		Reduced Peak Discharge, cfs		Revised High Water Mark, ft	
Control Location	Elevation, ft	Contributing	Non-contributing	Peak, cfs	Date, mo/day	High Water Mark, ft	Volume from March 1 to May 31 [c], ac-ft	Preexisting Condition	Postproject in GF and EGF	Preexisting Condition	Postproject in GF and EGF	Preexisting Condition	Postproject in GF and EGF	Preexisting Condition	Postproject in GF and EGF
Halstad (05064500)	826.65	15,205	6595	69,900	4/19	867.39	3,364,385	473,146	473,146	0.6	0.6				
Goose (05066500)	879.52	1039	164	8060	4/5		228,240	82,440		1.5	0.0				
Shelly (05067500)	841.14	220		4100	4/18	866.84	82,896	29,942		2.6	0.0				
Sandhill (05069000)	820.00	420		4360	4/20	902.50	105,608	38,145		1.7	0.0				
Crookston (05079000)	832.72	5270		27,500	4/18	861.12	1,012,892	365,853		1.3	0.0				
Ungauged Area		1187					222,799	80,474		1.3	0.0				
Drayton (05092000)	755.00	26,085	8715	124,000	4/24	800.56	5,707,269	1,317,629	1,317,629	0.9	0.9	50,000	54350	795.00	795.95
Grand Forks (05082500)	779.00	21,445	8655	127,000	4/18	833.35	5,016,820	1,070,000	473,146	0.9	0.4				
Turtle (05082625)	980.00	311		930	4/2		40,580	14,554	40,580	0.9	2.4				
Minto (05085000)	806.95	620	120	2100	4/20		81,850	29,355	81,850	0.9	2.5				
Grafton (05090000)	811.11	695		5150	4/21	826.37	131,965	47,329	131,965	1.3	3.6				
Argyle (05087500)	828.53	255		3800	4/19		66,930	24,004	66,930	1.8	4.9				
Ungauged Area		2699					369,124	132,386	369,124	0.9	2.6				
Emerson (05102500)	700.00	31,445	8755	129,000	4/26	792.56	6,339,660	794,580	794,580	0.5	0.5	80,000	80,000	789.52	789.52
Drayton (05092000)	755.00	26,085	8715	124,000	4/24	800.56	5,707,269	1,317,629	690,449	0.9	0.5				
Akra (05101000)	930.00	160		675	4/22		37,908		5589	0.0	0.7				
Neche (05100000)	809.69	3410		14,300	4/27	834.44	558,232		82,300	0.0	0.5				
Lake Bronson (05094000)	928.53	422		4100	4/20		110,170		16,242	0.0	0.7				
Ungauged Area		1408					−73,919			0.0	0.0				

[a] Data for the main stem from USACE (Table 2 included in Regional Red River Flood Assessment Report, Wahpeton, North Dakota–Breckenridge, Minnesota, to Emerson, Manitoba, January 2003); some values are from USGS.
[b] From USGS. The values are the maximum discharges presented in the daily stream flow data.
[c] Computed based on the flow hydrographs from USGS.

depths of water needed for storage in the individual watersheds ranged from 0.2 to approximately 4.9 inches, with the maximum depth occurring in the subwatershed upstream of the USGS Argyle gauging station. For both the existing conditions and the postproject conditions, if the estimated volumes of water listed above could be regulated, the 1997 flood crests along the Red River would be lowered 3.0–7.0 ft (0.9–2.0 m).

These preliminary storage volume estimates indicated that the Waffle concept warranted further investigation. It is important to remember that these were preliminary estimates and were based on keeping the Red River from reaching major flood stage. In reality, the Red River flood stage would not have to be reduced this much to prevent a significant amount of flood damage. If the river stage could have been reduced enough to prevent the dikes from being overtopped in Grand Forks during 1997, requiring a reduction of perhaps only a couple of feet, hundreds of millions of dollars in flood damage may have been prevented. Of course, these results were used only to gain an idea of the storage volumes necessary to achieve a significant reduction in flooding. The actual evaluation of Waffle effectiveness was conducted using hydrologic and hydraulic models developed through the project and discussed later in this report.

2.3 Identification of Storage Areas and Volumes

2.3.1 Methodology

With nearly 36,000 square miles of the RRB to assess with regard to water storage potential, identifying storage areas suitable for the Waffle concept was a challenge. After conducting a survey of existing data, it was determined that the most expedient method of identifying storage areas was to use GIS coupled with the best available digital data sets. The data sets identified for use in this effort include digital elevation models, the hydrologic network (rivers, streams, and lakes), cultural features, the transportation network (roads and railways), Public Land Survey System (PLSS) data, and satellite imagery. The following section provides an overview of the methodology used to evaluate storage areas and volumes, as well as key results. A detailed description of the methodology is contained in Appendix B.

The storage volume for the RRB was calculated on a subwatershed-by-subwatershed basis. Such an approach was taken to allow for integration of the results with other watershed-modeling efforts conducted in the project. Out of the 28 subwatersheds in the U.S. portion of the RRB, only 26 were considered for water storage (Figure 9). The Devils Lake and Red Lake Subwatersheds were eliminated because of little to no drainage, or controlled drainage, into the Red River. In addition, only the lower portion of the Otter Tail River watershed was considered for water storage because of the high number of closed basins and limited drainage in the upper part of the watershed.

The evaluation of Waffle storage within the RRB was based on the fact that the suitability of land for Waffle-type storage is controlled primarily by the amount of relief across the parcel (difference in maximum and minimum elevation of the parcel) and the existence of a feature, anthropogenic or natural, that will hold an appreciable volume of water in place, such as a road.

Figure 9. Location of subwatersheds evaluated for Waffle storage in U.S. portion of RRB.

Lower local relief provides a greater storage potential in individual storage sections (Figure 10). Although a parcel of land may be topographically suited for water storage, there may be physical, cultural, or economic variables that may either exclude the land from water storage or allow for the prioritization or ranking of the land against other suitable parcels. Physical and cultural features were taken into account in determining suitable storage parcels.

To determine storage locations for each watershed in the RRB, the landscape was divided into parcels based on the PLSS. The PLSS divides the landscape into 1-square-mile units called sections. Because roads generally follow the PLSS system and often surround individual sections, potential storage areas and storage volumes were identified on a square-mile basis.

To identify the location of potential storage areas, GIS was used to overlay the PLSS-based network of roads within the RRB over digital elevation data obtained from the USGS National Elevation Dataset (NED). NED is a raster product assembled and designed to provide national elevation data in a seamless format with a consistent datum, elevation unit, and projection. Although some 10-meter-resolution data are available, the entire RRB is represented by

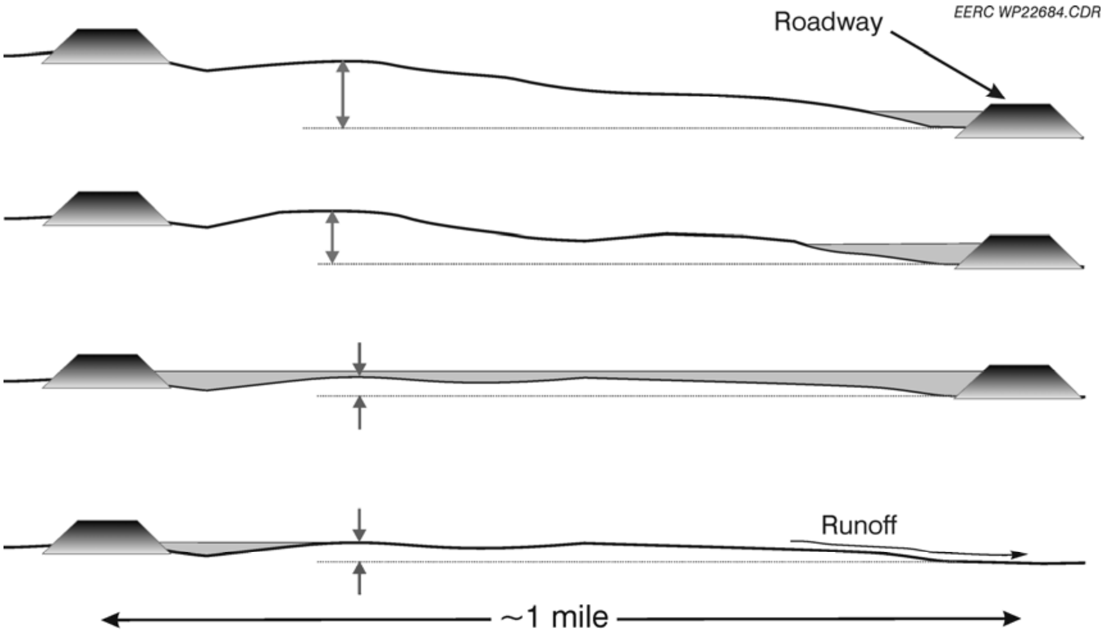


Figure 10. The importance of local relief and raised roadways in identifying potential storage areas.

30-meter-resolution digital elevation data. This means that the basin is represented by a gridwork of cells measuring 30 meters on each side, and each of these cells is assigned an average elevation value. Figures 11 and 12 depict a small section of these data represented using a gradational color scale. The 30-meter resolution of these data means that there is one elevation value to represent 900 square meters (9688 ft^2; 0.22 acres) of land surface; topographic variability within this region is minimized. Higher-precision data sets were available for small portions of the basin; however, these data sets focused on the relatively narrow floodplain bands along tributaries and within municipalities and do not include the upland areas beneficial for water storage.

To conduct a basinwide assessment of storage areas, a set of criteria was used to eliminate areas that may not be suitable for water storage. These include the following:

1. A section must not contain water bodies such as lakes, ponds, water treatment ponds, swamps, and sloughs.

2. A section must not contain watercourses such as rivers and larger streams/creeks.

3. A section must not contain any of the following anthropogenic structures that would be submerged by water: towns, airports, landing fields, cemeteries, churches, farmsteads, and schools.

4. A section must be bounded by raised section roads, highways, or railroads.

5. Topographic maps must provide road survey points for a section.

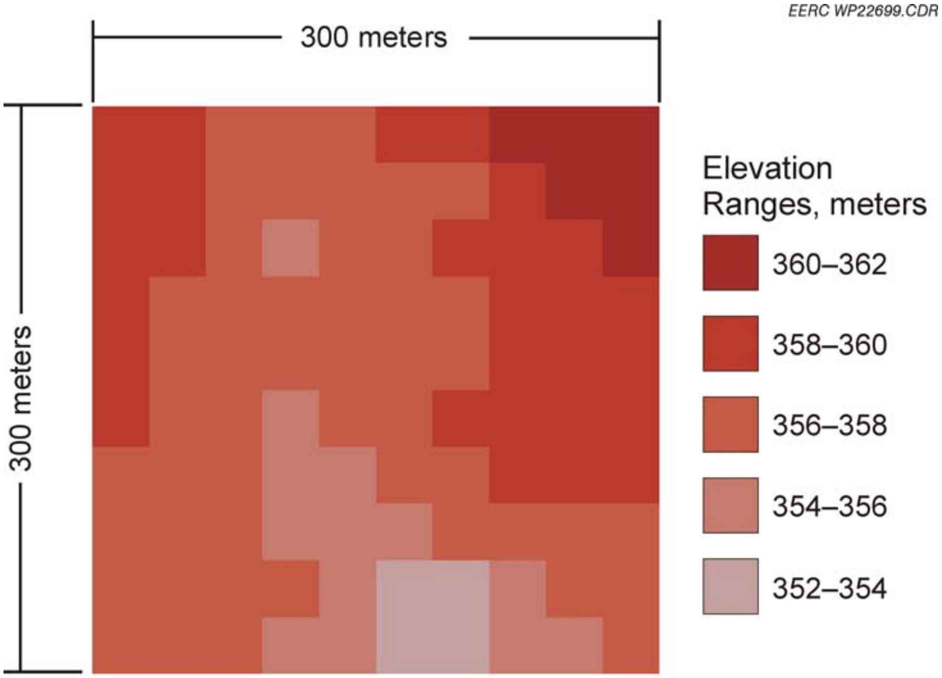


Figure 11. Plan view representation of grid-based digital elevation data.

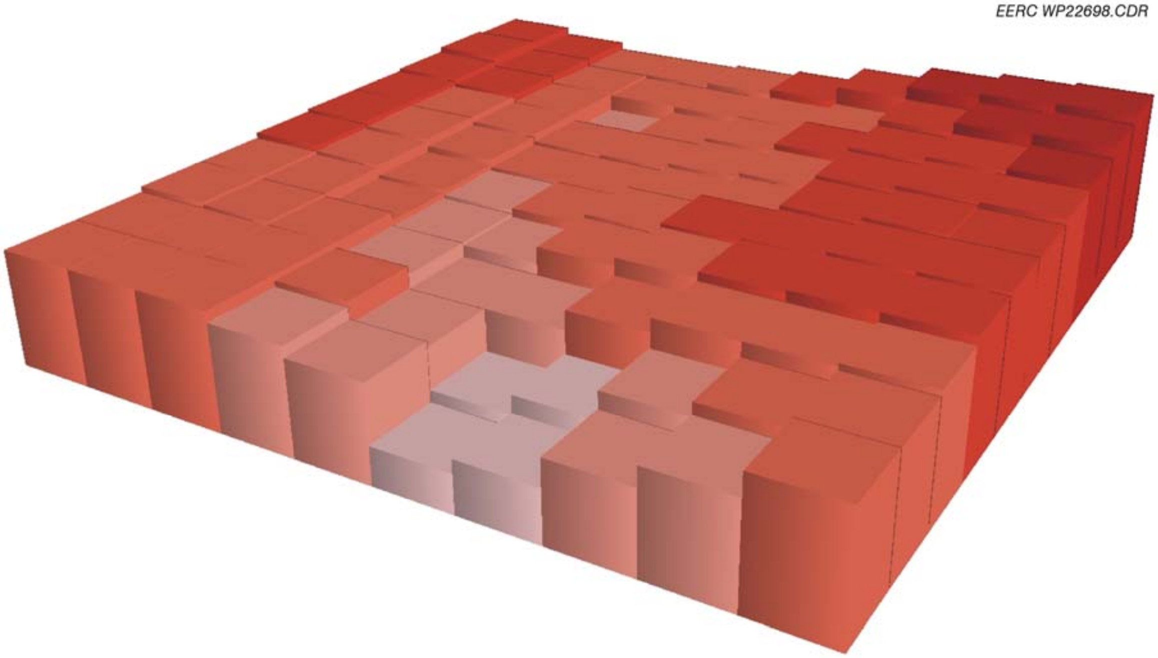


Figure 12. Three-dimensional representation of grid-based digital elevation data.

In actuality, a section not meeting all of these criteria may sometimes still be suitable for water storage (i.e., a section contains a school, but it would not be affected by water storage). However, because of the large number of sections evaluated by this study, the project team decided to err on the conservative side rather than conduct a detailed evaluation of each potential storage area.

Both digital topographic maps and digital vector data sets of water bodies were used to identify whether or not a section contained lakes or ponds. Rivers and streams were recognized with the watercourse data set. Sections containing water bodies were removed from consideration because lakes and ponds naturally store water; hence, these sections have no need for Waffle storage. Large watercourses eliminated sections because of the cost and difficulties associated with their control.

Anthropogenic structures were identified by evaluating the digital topographic maps and DOQ (digital orthophoto quadrangle) data sets for a given section. The digital topographic maps, DOQs, and PLSS data sets were used to identify sections with roads that had the potential to contain water. Highways, interstates, and railroad tracks are all built on well-maintained, raised beds and are ideal as control structures for water. However, not all secondary roads would be suitable for water retention. Only section roads were considered sufficient for storage purposes because nonsection roads may not be maintained or do not have raised road beds.

Road elevation data from topographic maps were used to estimate the volume of water that could be potentially stored by a section. Most sections had point elevations given in each corner and midway in between for a total of eight road elevations per section. In some cases, not all of these elevations were given, especially if section roads were not represented. If a road appeared to be in the topographically lowest part of the section and elevation data were not available, a determination was made to either estimate a road elevation or use the smallest of the available road point elevations. An ideal section would have no water bodies, watercourses, or cultural features, and it would be completely surrounded by raised roads with all eight elevation points. One caveat with this methodology is that it assumes that there are no road elevations lower than the 8 points listed on the topographic map. Although this may not be the case, there were no other available sources of road elevation data, and it was infeasible to collect these data for the entire RRB. Figure 13 illustrates how road location and elevation data were combined with digital elevation data to estimate storage depth for individual sections. The storage depths were multiplied by the area of each corresponding pixel to estimate storage volumes, which were then added for each section.

Because it was unrealistic to calculate storage volumes for each individual section throughout the RRB, a statistical methodology was utilized to determine representative storage volumes for each subwatershed. This approach entailed the random selection of 20 sections within each RRB subwatershed for calculation of storage volume. The statistical variability in storage volumes was then used to determine how many additional sections would have to be analyzed to come within 20% of the value if all sections in the watershed were evaluated. For

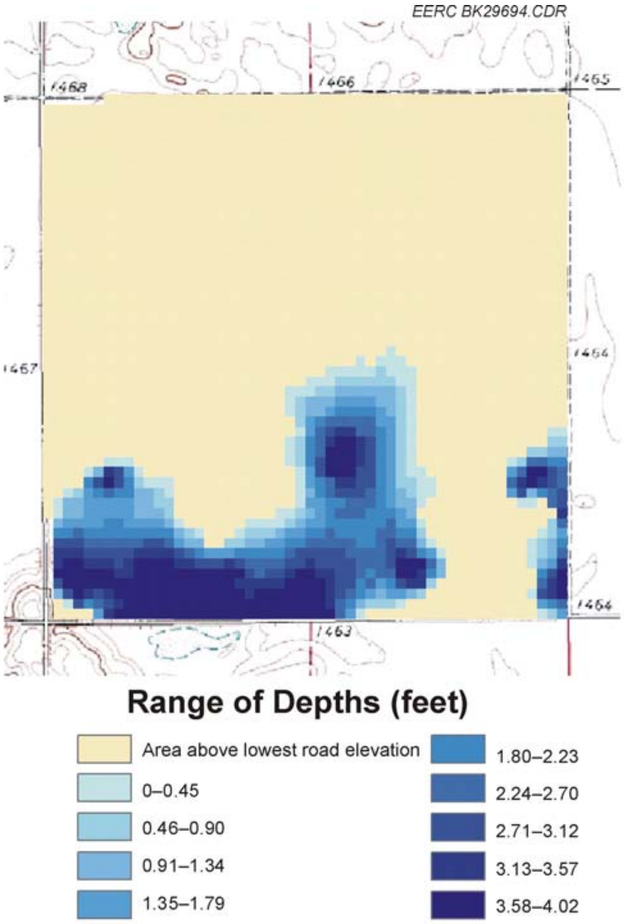


Figure 13. An example of storage depth calculations for a PLSS section using road elevation data and digital elevation data.

example, the total number of sections within the Red Lake River Watershed is 1539; however, only 88 sections needed to be evaluated to come within 20% of the volume that would be determined using all sections. Any sections that were truncated (i.e., by boundaries) were eliminated from the storage volume calculations unless their area was greater than 0.75 square miles. A total of 3732 individual sections throughout the RRB were ultimately analyzed using this approach. A breakdown of the number of sections analyzed per watershed is given in Table 3.

To determine the approximate storage volumes of sections that were not explicitly analyzed in the above methodology, the average storage volumes of the analyzed sections were determined based upon relief categories. Relief was chosen as a means of categorizing storage volumes based on analysis of sample sections, which indicated an inverse relationship between storage volume and terrain relief. In general, the total storage potential decreases as the relief increases for a section. To better identify the relationship between relief and storage potential, each section with a volume greater than zero was plotted as a function of its elevation relief and

Table 3. Number of Square-Mile Sections Evaluated per Watershed to Estimate Waffle Storage Volumes. A total of 3732 sections were evaluated throughout the RRB.

Watershed	Number of Sections Evaluated	Watershed	Number of Sections Evaluated
Bois de Sioux	121	Park	83
Buffalo	127	Pembina	134
Clearwater	154	Red Lake	88
Elm-Marsh	74	Roseau	312
Forest	256	Sandhill-Wilson	146
Goose	123	Snake	63
Grand Marais Creek	100	Thief	145
Lower Red	196	Turtle	101
Lower Sheyenne	100	Two Rivers	74
Maple	165	Upper Red	115
Middle Sheyenne	202	Upper Sheyenne	383
Mustinka	77	Western Wild Rice	119
Otter Tail	170	Wild Rice	104

corresponding potential storage volume. Figure 14 is a graph of the plotted sections that illustrates the inverse relationship between storage potential and relief. A cumulative distribution of storage based on relief was created to determine if readily identifiable relief categories existed as a function of storage. Figure 15 illustrates this distribution. Four relief categories were identified from the distribution: 0 to 2, 2 to 4, 4 to 10, and 10 to 100 plus meters. These

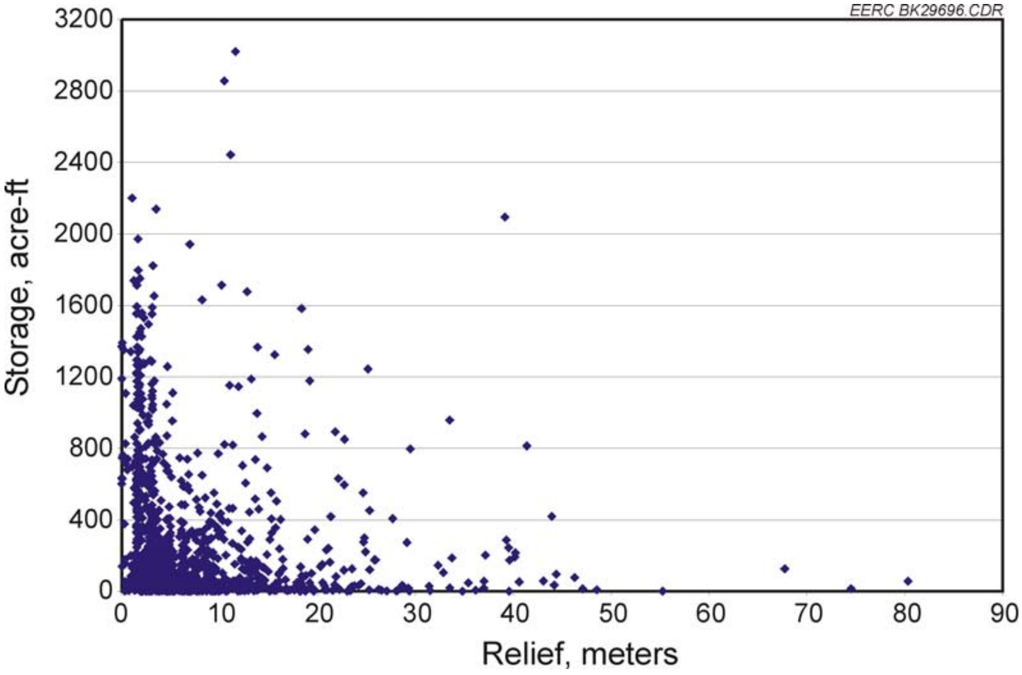


Figure 14. Section relief plotted against potential storage.

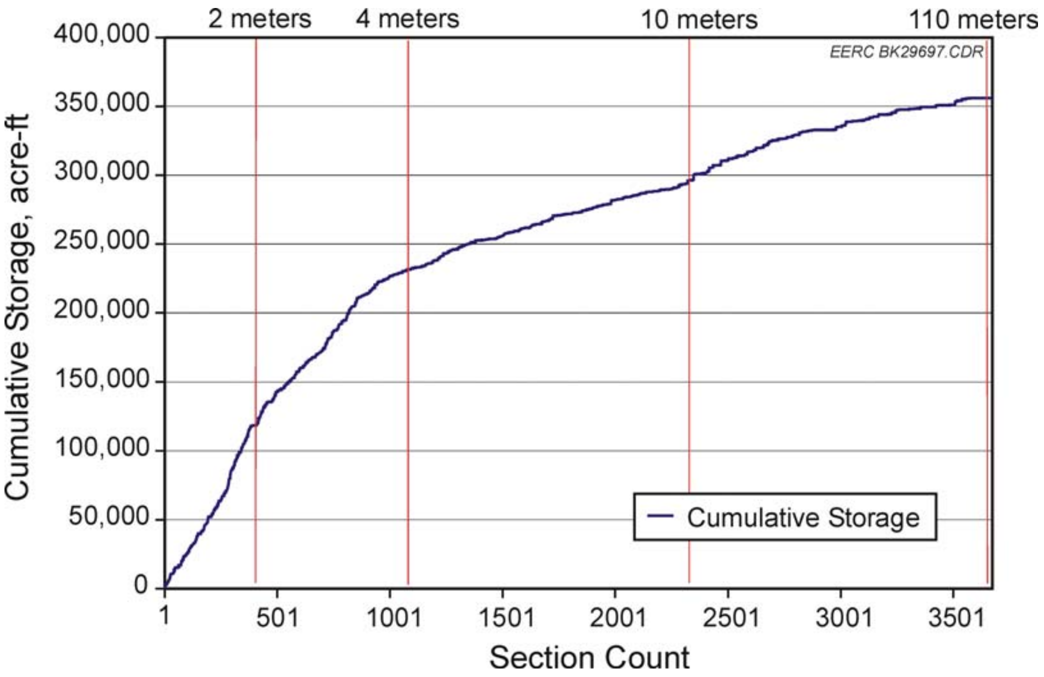


Figure 15. Cumulative distribution graph for potential storage with over 3700 sections evaluated for the RRB.

categories were chosen based on significant changes in slope of the curve, which indicates the rate of change of storage with relief.

Once the average storage volume per relief category was determined for each watershed, the number of sections greater than 0.75 square miles in each relief category was multiplied by the corresponding average volume to estimate the total potential storage volume. The total volumes were added for each relief category to determine a volume for each watershed.

2.3.2 Adjustment of Storage Volumes

The Waffle storage volumes determined by the above approach are considered the maximum potential storage, assuming no roads are raised. In practice, Waffle storage areas would likely include freeboard between the stored water surface and the lowest point on the surrounding roads. In addition, the maximum storage volume estimates include natural storage, or the water that does not contribute to downstream flooding because it remains trapped in small pools on the landscape and does not drain. To gain a better estimate of Waffle storage volumes, the original storage estimates were reduced to account for freeboard and natural storage.

To determine an appropriate volume reduction to account for freeboard, four subwatersheds were selected for comparison purposes, including the Forest River, Lower Sheyenne River, Red Lake River, and Wild Rice River (MN) subwatersheds. These four subwatersheds were selected because they encompassed the range of physical characteristics (size, shape, topographic variation, land use/land cover, and distribution of waterways and lakes) exhibited by the subwatersheds of the RRB. The same technique used to calculate the original storage volume estimates was applied to these subwatersheds, except the lowest road elevation was further reduced by 1 foot to account for 1 foot of freeboard.

Three of the four watersheds had a reduction in storage of 42%–45% as a result of including a 1-foot freeboard. The fourth watershed, the Lower Sheyenne, had a storage reduction of only 23%. A statistical test (t-test) was performed on the freeboard results from all four watersheds for comparison with the remaining watersheds in the RRB. It was determined that a 15% to 65% reduction was necessary in the remaining watersheds to account for freeboard within a 90% confidence interval. Based on this information, it was decided that two methods would be used to account for freeboard. One method used a conservative approach and reduced storage volumes by 50% to account for freeboard. The other method used a less conservative approach and reduced storage volumes by 25% to account for freeboard. These percentages were within 5% of the range exhibited by the test watersheds and, therefore, were deemed representative.

In addition, the average storage volume of each section was further reduced to account for natural storage. Based on values listed in the literature, measurements of natural or depressional storage range from a ¼- to ½-inch depth of water for pervious surfaces with gentle to moderate slopes (Handbook of Applied Hydrology, 1964). Over an entire section, the volume occupied by a half inch of water is approximately 25 acre-ft and 12.5 acre-ft for a quarter inch of storage. Therefore, both a conservative and moderate approach were taken to adjust for natural storage. For each watershed, both, 25 acre-ft and 12.5 acre-ft were multiplied by the number of whole sections (≥ 0.75 square miles) and subtracted from the freeboard estimate of storage. The conservative reduction of 25 acre-ft per section was subtracted from the conservative freeboard estimate (50% reduction). The less conservative 12.5 acre-ft estimate of natural storage was subtracted from the moderate storage estimate (25% reduction). In reality, since many fields in the region have been laser-leveled and many of the naturally occurring depressions have been filled or drained, natural storage estimates may be closer to the lower estimate or, possibly, even lower.

One final adjustment was made to the storage volume estimates—the removal of PLSS sections within the 1997 floodplain. Unlike the previous storage adjustments, this one was applied only to the most conservative storage estimates. The assumption was that in spring seasons with extreme runoff, areas within this floodplain may be flooded or only available for storage toward the end of flooding events. Ideally, if upstream storage was implemented, many of the areas within this floodplain would then be available for storage; however, in keeping with a conservative approach to estimating storage, all areas within the 1997 floodplain were eliminated from consideration. USACE provided GIS files outlining the floodplain as depicted on satellite imagery collected during the 1997 flood. The elimination of storage sections within the 1997 floodplain significantly reduced the estimated storage potential of some watersheds since these areas tend to be flat and have a high potential for storage.

The original storage volume estimates and adjusted estimates using conservative assumptions and moderate assumptions are listed in Table 4 and shown in Figure 16. The most conservative Waffle storage volume estimate for the RRB, and that explicitly modeled in

Table 4. Original and Adjusted Storage Volume Estimates. The original values were not adjusted to account for freeboard, natural storage, or the 1997 floodplain. The moderate storage estimates included a 25% volume reduction to account for freeboard and a 12.5-acre-ft reduction per section to account for natural storage. The highly conservative storage estimates include a 50% volume reduction to account for freeboard, a 25-acre-ft reduction per section to account for natural storage, and elimination of all storage areas in the 1997 floodplain.

Watersheds	USGS 8-digit HUC	Storage Estimate No Adjustments, acre-ft	Moderate Storage Estimate, acre-ft	Highly Conservative Storage Estimate, acre-ft
Bois de Sioux	09020101	108,000	71,100	24,900
Buffalo	09020106	89,000	56,700	17,600
Clearwater	09020305	64,000	35,200	11,400
Elm-Marsh	09020107	334,000	240,500	93,100
Forest	09020308	63,000	39,100	8,000
Goose	09020109	109,000	70,700	19,100
Grand Marais-Red	09020306	167,000	119,700	30,900
Lower Red	09020311	222,000	156,800	49,700
Lower Sheyenne	09020204	344,000	243,000	38,200
Maple	09020205	152,000	99,800	17,500
Middle Sheyenne	09020203	99,000	56,100	2,700
Mustinka	09020102	39,000	21,800	5,700
Otter Tail*	09020103	9,000	4,800	1,600
Park	09020310	143,000	97,600	29,200
Pembina	09020313	149,000	93,500	16,100
Red Lake	09020303	124,000	81,500	30,400
Roseau	09020314	99,000	63,400	12,400
Sandhill-Wilson	09020301	139,000	94,100	37,100
Snake	09020309	55,000	34,000	7,300
Thief	09020304	100,000	65,800	20,500
Turtle	09020307	69,000	45,400	6,700
Two Rivers	09020312	87,000	56,800	16,400
Upper Red	09020104	120,000	84,400	37,000
Upper Sheyenne	09020202	88,000	48,600	5,700
Western Wild Rice (North Dakota)	09020105	210,000	137,000	28,600
Wild Rice (Minnesota)	09020108	114,000	71,000	15,600
	Total Storage:	3,296,000	2,188,400	583,400

* Only a small portion of the Otter Tail Watershed was evaluated for Waffle storage (see Figure 9).

this study, is approximately 583,400 acre-ft. The moderate storage volume estimate for the RRB is 2,188,400 acre-ft. The original total storage volume estimate was 3,296,000 acre-ft. The reduction of storage volumes to account for freeboard and natural storage, as well as areas located in the 1997 floodplain, had a dramatic reduction in storage volumes compared to initial estimates. The initial estimates indicated that more than half of the watersheds had potential storage capacities of 100,000 or more acre-ft of water, while most of the adjusted storage capacities are less than 100,000 acre-ft. For comparison, the conservative Waffle storage estimate for the RRB (583,400 acre-ft) is almost 1/6 of the initial estimate.

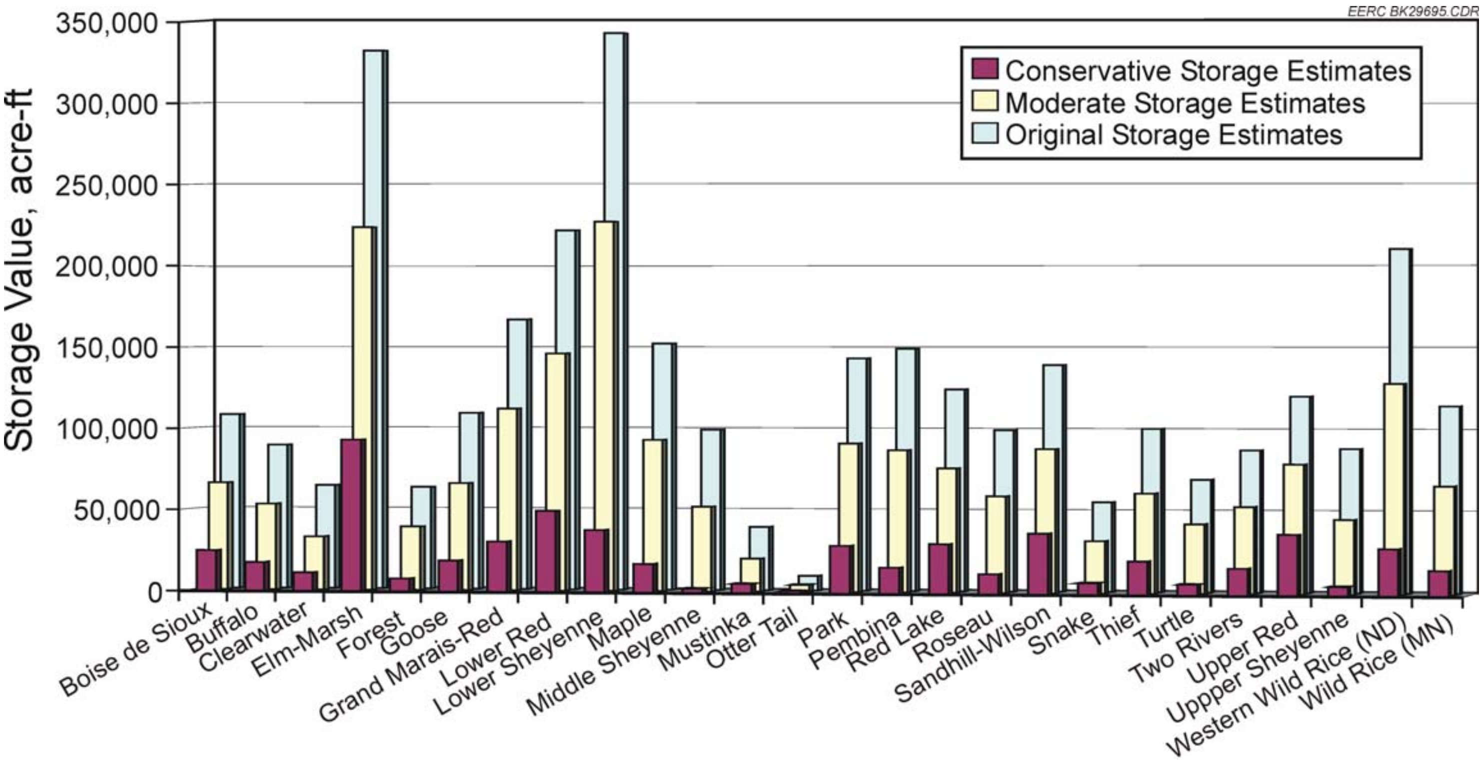


Figure 16. Comparison of Waffle storage estimates for the RRB watersheds.

In addition to the storage reductions applied to more accurately represent the physical characteristics of the Waffle concept, additional storage reductions were performed to account for less-than-optimal participation rates. These reduced volumes corresponded to 75% to 50% of the conservative Waffle storage estimate (583,400 acre-feet). The various Waffle storage scenarios (and corresponding storage volumes) modeled by this study are discussed in more detail in Section 2.4.5 of this report.

Although the original storage volume estimate was not considered in the modeling of Waffle storage effects, it is provided to illustrate the potential Waffle storage volume if minor modifications were made to existing roads. Throughout evaluation of individual storage sections, members of the Waffle team observed that in many instances, the limiting factor in storage was only a small section of roadbed that was lower in elevation than the remaining roads. If these sections of road were raised, in many cases by only a foot or two, storage volumes could significantly increase. The raising of low-lying road sections may also help prevent future road washouts, since it is typically these areas that are overtopped and washed out during spring and summer floods.

As a comparison, the previously discussed USGS estimate of the water storage potential in the Wild Rice River Watershed (of Minnesota) was 80,879 acre-ft (Sanocki, 2000). The original storage estimate, without accounting for freeboard, natural storage, or the 1997 floodplain was 120,000 acre-ft. The adjusted estimates using the conservative assumptions and moderate assumptions were 15,600 and 71,000, respectively. The adjusted storage estimate using moderate assumptions is very close to the USGS estimate; however, additional comparisons would be needed to draw conclusions regarding the accuracy and precision of either approach.

2.3.3 Distribution of Storage

One of the key goals of the Waffle project was to determine the reduction in RRB tributary flows as a result of Waffle storage. The Soil and Water Assessment Tool (SWAT) was the hydrologic model chosen to accomplish this goal (see Section 2.4 for further details). In order to evaluate the effects of Waffle storage, the SWAT model required the location and volume of individual Waffle storage parcels. Water storage was initially calculated on a watershed-by-watershed basis and, although this provides information about storage volumes, more specific information about storage distribution was necessary for the SWAT model. As a result, storage had to be distributed among PLSS sections within the basin.

It was decided that the most conservative storage volume estimates would be explicitly modeled using SWAT. As such, the distribution of storage back to the landscape was applied using only the lowest storage volume estimate (583,400 acre-ft).

The even distribution of water among all sections was determined to be unrealistic since many sections were inappropriate for water storage (i.e., if they contained a cultural feature) and sections with less topographic relief are more likely to store water. Therefore, each category was assigned a value reflecting the probability that sections in that category would have adequate storage potential. A high probability of 95% was assigned to the 0–2-meter relief category; a moderate probability of 75% to the 2–4-meter category, and a low probability of 25% for the 4–

10-meter category. A zero probability was assigned to the 10- to 100-meter-plus category because it was judged to have a very poor potential for efficient water retention.

The distribution of water storage was limited to those sections with areas greater than or equal to 0.75 square miles. Smaller sections were left out because the chosen method for distributing the storage does not account for size of section. Consequently, the estimated storage potential for a watershed was adjusted to not include contributions from these "partial" sections.

The adjusted water storage volumes were divided by the number of sections in the three lowest-relief categories to determine the average storage per section for a watershed. In order to assign a unique storage value to each category, the average storage per section was multiplied by a weight function. The following equation provides an example of the calculation for the 0- to 2-meter relief category:

$$\frac{95\% \times (A + B + C)}{95\% \times A + 75\% \times B + 25\% \times C} \times \frac{\begin{array}{c}\text{(Total Volume Less}\\ \text{Very Poor Category)}\end{array}}{(A + B + C)} = \begin{array}{c}\text{Average Storage}\\ \text{Per Section}\end{array} \qquad \text{[Eq. 3]}$$

A, B, and C represent the number of sections that fall in the 95%, 75%, and 25% probability categories, respectively. The term on the left represents the weight function. The above equation can be simplified to the following:

$$\frac{95\%}{95\% \times A + 75\% \times B + 25\% \times C} \times \begin{array}{c}\text{(Total Volume Less}\\ \text{Very Poor Category)}\end{array} = \begin{array}{c}\text{Average Storage}\\ \text{Per Section}\end{array} \qquad \text{[Eq. 4]}$$

In Equation 3, the first term on the left-hand side was referred to as the geographical distribution factor for the 0- to 2-meter relief category. The geographical distribution factor takes into account the number of sections and storage probabilities for each relief category. The right-hand term represents the estimated storage potential for a watershed minus the storage potential from the 10–100-meter relief category and sections smaller than 0.75 square miles. Small sections were removed from consideration, because the chosen distribution method does not account for section size. Subsequently, the method assumes all sections to be approximately 1 square mile.

Geographical distribution factors were calculated for the three lowest-relief categories for each watershed. The application of these factors in Equation 3 resulted in the calculation of storage volumes for each of the three relief categories for every watershed. Again, the distribution of storage was only applied to the most conservative storage estimates.

In summary, storage potential for each watershed was adjusted to exclude storage from partial sections (less than 0.75 mi^2) and sections with terrain relief equal to or greater than 10 meters. Three geographical distribution factors were applied to the adjusted storage potential for each watershed, which resulted in storage estimates for the three lowest-relief categories. The resulting volumes were distributed to sections according to their relief classification. If any of the sections contained urban areas or were located within the 1997 floodplain, storage amounts were not assigned to them.

In addition to determining potential storage volumes, the land area affected by Waffle storage was estimated. This was determined in each subwatershed by dividing the conservative and moderate storage volume estimate by the average depth of water for each relief category. The average water depths for each relief category were determined based on the depths observed in the individual sample sections analyzed for the statistical approximation (including freeboard). Using this approximation, the total estimated land area that would be flooded if the Waffle were fully implemented ranges from 334,200 to 1,170,500 acres based on conservative and moderate storage volume estimates, respectively. This is equivalent to 1.5% to 5.2% of the total land area in the U.S. portion of the RRB (excluding the Devils Lake subwatershed).

2.3.4 Methodology Validation

The methodology described above (a.k.a. NED/digital raster graphics [DRG] method) was developed using the most up-to-date data sets for the RRB; however, the question still remained as to how the results would vary if high-resolution elevation data were available. Therefore, in an attempt to validate the results, the EERC, with support from the NRCS mapping office in Texas, financed the collection of Lidar (light detection and ranging) data for the Forest River Watershed. Aircraft equipped with Lidar transmit high-intensity light toward the ground during flight. As the light interacts with the ground, some of the light is reflected back to a receiver on the aircraft. The time for the light to travel to the target and back varies directly with the distance between the target and plane. Very advanced positioning equipment and ground reference points allow for the conversion of these distances to elevation data.

The Lidar data collected for the Forest River Watershed have a vertical accuracy of ±15 cm (5.9 inches) and a horizontal resolution of 1 meter (3.28 ft). Elevation data with a horizontal resolution of 1 meter are capable of differentiating raised roadbeds from the surrounding terrain, which was not possible with NED. Because of the large number of 1-meter grid cells (~ 2.26 billion), the Lidar data were resampled to a 3-meter grid, thereby reducing the number of grid cells to approximately 251 million. Raised road beds are still represented in the new grid as most roads are between 3.66 (single lane) and 9.15 meters (double lane) wide (i.e., 12 to 30 feet).

The ability to distinguish roadbeds in the elevation data provides an opportunity to estimate potential storage behind them. A hydrologic fill algorithm was performed on the Lidar data set to identify these areas and associated storage volumes. This is a means of calculating the inherent nature of the storage volume in sinks using GIS. Figure 17 illustrates the results of the hydrologic fill on the Forest River Watershed. The data resulted in some unintended storage areas. For example, passages under bridges cannot be distinguished using the Lidar data set. As a result, the software artificially dammed water behind the bridges. Sinks associated with these artificial dams were in turn removed.

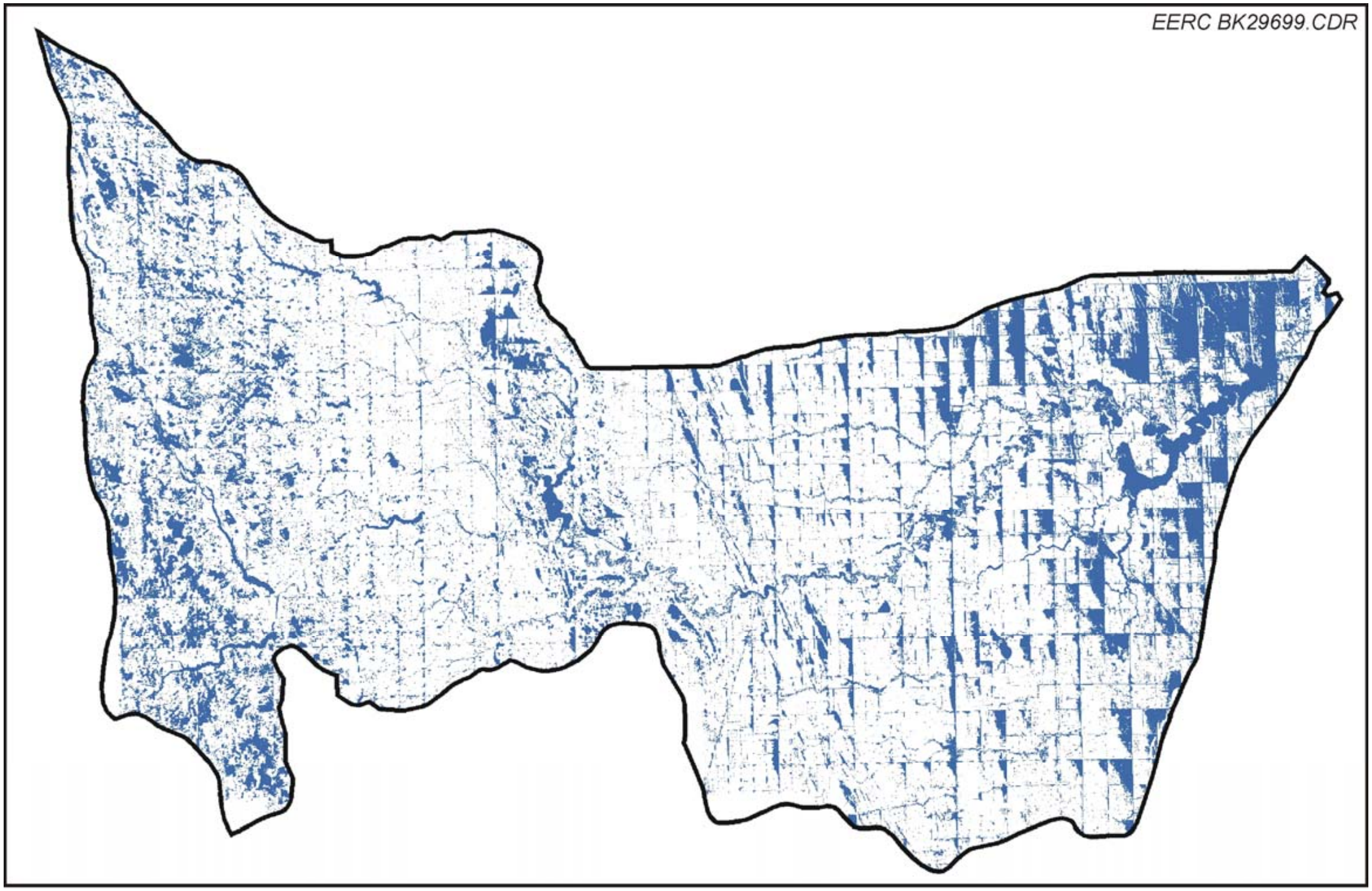
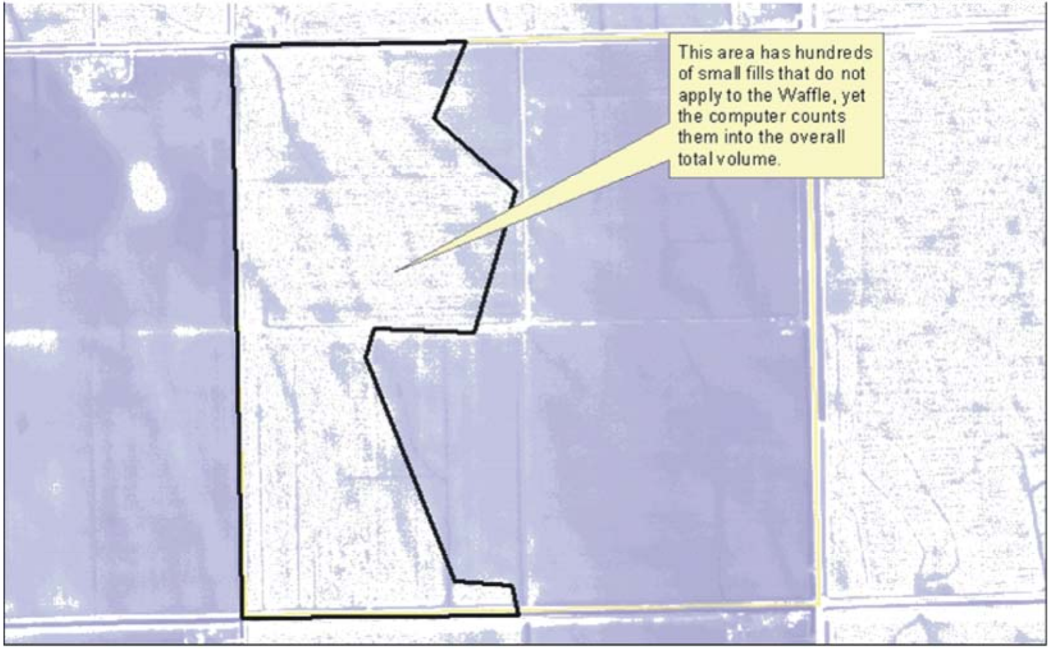


Figure 17. Results of a hydrologic fill of the Forest River Watershed.

Conditions were imposed on the results from the hydrologic fill in order to improve volume estimates and isolate desired sinks. Hydrologic sinks were limited to grid cells with depths greater than 20 cm (18 in.) and sinks smaller than 10 acre-ft were removed from consideration (Figure 18). Also, sinks associated with large water bodies and those falling within the boundaries of towns or rivers were eliminated from the group. The majority of sinks left after the application of these conditions were the result of roads (Figure 19). Hence, these sinks could be used to provide an assessment of the Waffle storage potential for the Forest River Watershed.

The storage volumes for the remaining Lidar sinks were adjusted to account for a 1-ft freeboard around the roads. If the freeboard adjustment caused the capacity to drop below 10 acre-ft, these sinks were eliminated from the group. These adjusted storage volumes were summed together to provide an approximation of total storage potential for the watershed, which amounted to approximately 44,700 acre-ft. For comparison, the Forest River Watershed storage estimate before accounting for freeboard, natural storage, and the 1997 floodplain was 60,000 acre-ft. The moderate storage estimate, which considered 12.5 acre-ft of natural storage and a 25% volume reduction to account for freeboard, was 39,100 acre-ft. The most conservative estimate, which did not include areas in the 1997 floodplain, assumed a 25-acre-ft storage reduction per section and included a 50% volume reduction to account for freeboard, was 8000 acre-ft. Similar to the comparison with the USGS results, the NED methodology with the moderate storage volume reductions most closely matches the Lidar storage estimate. Again, it appears that the most conservative storage estimates using the NED methodology may significantly underestimate water storage potential.

EERC BK29698.CDR



This area has hundreds of small fills that do not apply to the Waffle, yet the computer counts them into the overall total volume.

Figure 18. Example of sinks not applicable to Waffle storage.

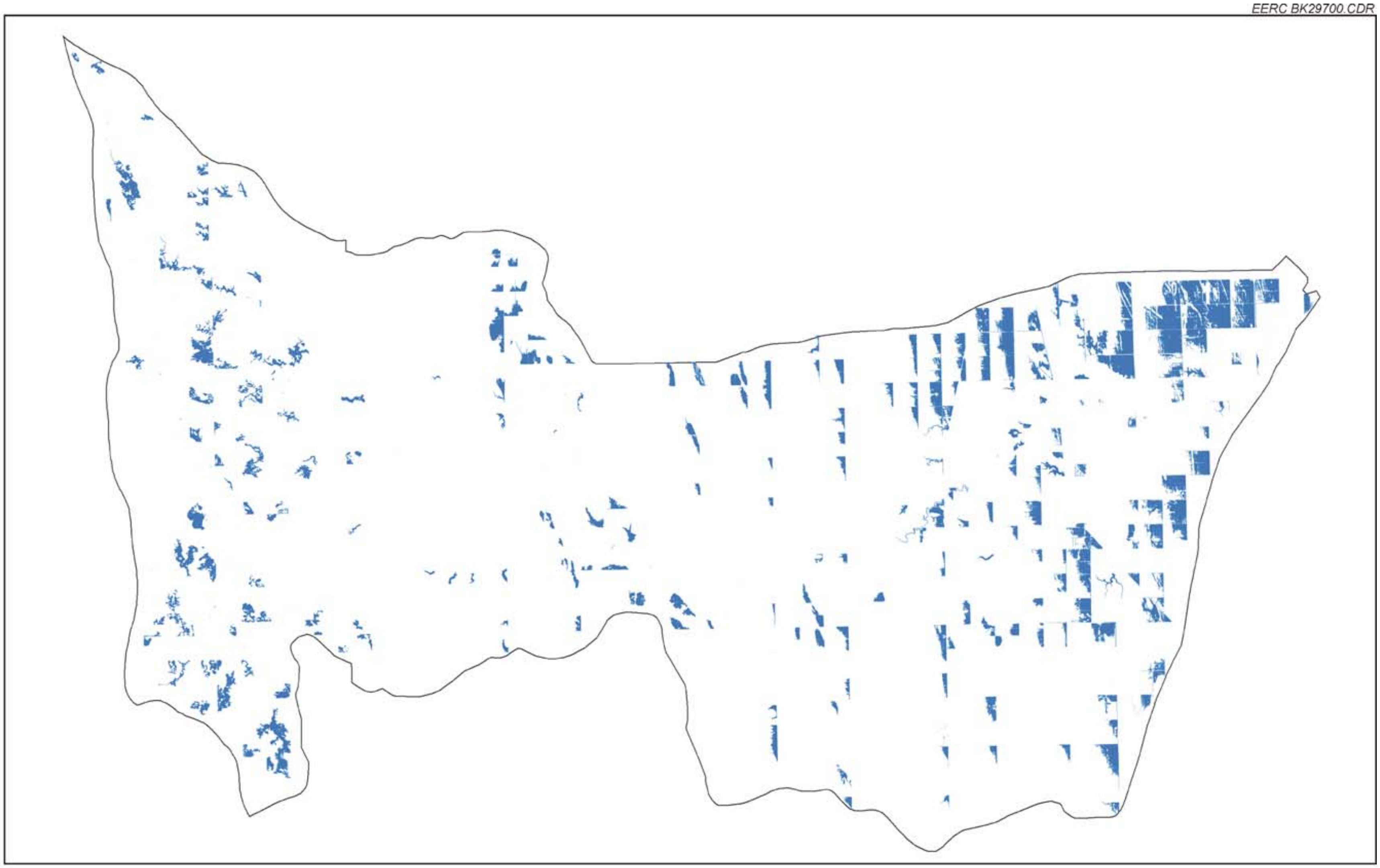


Figure 19. The final representation of sinks for the Forest River Watershed.

2.4 Model Development

2.4.1 Background

Hydrologic and hydraulic models play a key role in evaluating the various structural and nonstructural flood mitigation measures proposed throughout the RRB (Halliday and Jutila, 2000; International Joint Commission, 1997). In the past few decades, numerous models relevant to flood mitigation of the Red River have been developed (see Appendix C). However, it would have been unrealistic to directly use these models to evaluate the Waffle concept because 1) they were developed for other objectives; 2) they have a different modeling scope, making it impossible for accurate comparison; 3) their parameters were not correlated with land use and other watershed management practices; and 4) they were not applicable basinwide. Thus, in order to evaluate the impact of Waffle storage on flow reductions in the Red River and its tributaries, as well as stage reductions at key points along the Red River, a consistent modeling framework was developed for the RRB.

This entailed the development of hydrologic models for each of the subwatersheds located within the U.S. portion of the RRB (excluding the Devils Lake Watershed), as well as development of a hydrodynamic model of the main stem Red River. The following section describes the conceptual approach utilized by the EERC in model development, explains the models utilized by this study as well as their development and calibration and, finally, describes the results determined through the modeling effort.

2.4.2 Integrated Main Stem/Subbasin Conceptual Model

Although various flood mitigation analyses have been conducted in the past few decades, they were designed for different modeling objectives, and the data sets used to develop the models are not consistent. In addition, the models do not directly link land use and land management practices to the model output. As a result, a new modeling approach for evaluation of the Waffle flood mitigation concept was necessary. This approach entailed coupling two different types of models to conduct the first comprehensive evaluation of a flood mitigation strategy for the entire RRB (Figure 20).

The first component of this approach was the development, calibration, and utilization of hydrologic models for 27 of the 28 subwatersheds in the U.S. portion of the RRB using SWAT. The Devils Lake subbasin was not modeled because it is a closed basin and does not contribute flow to the Red River. Figure 21 shows the hydraulic connectivity of these subwatersheds, as defined by their USGS 8-digit HUCs. The watershed name and drainage area corresponding to the 8-digit HUC is listed in Table 5. These hydrologic models were used to evaluate flow reductions in the RRB tributaries as a result of implementing Waffle storage throughout each watershed during a 1997-type flood event.

The second component of this approach was the evaluation of flood crest reductions along the Red River as a result of tributary flow reductions achieved by Waffle storage. This required the development and calibration of an unsteady-state (hydrodynamic) model, which was

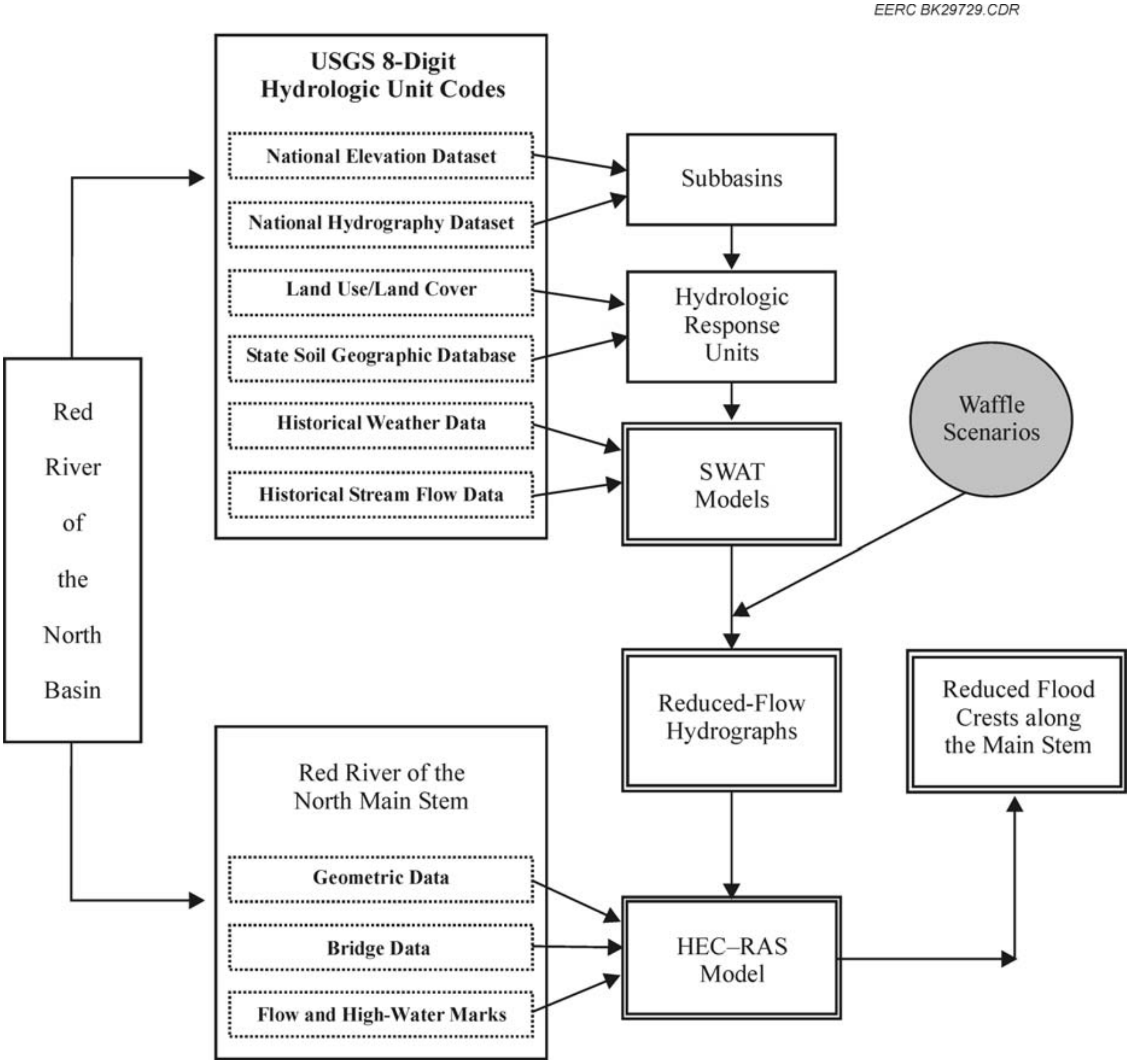


Figure 20. Conceptual model scheme for the RRB.

compiled using the HEC–RAS model. The development of the HEC–RAS model was a joint effort with USACE.

Although this integrated modeling approach was developed for evaluation of Waffle storage, a similar approach could be used to evaluate a multitude of structural and nonstructural flood mitigation options throughout the RRB. Scenarios may include evaluation of structural measures such as improvements to existing retention ponds and culverts or construction of new

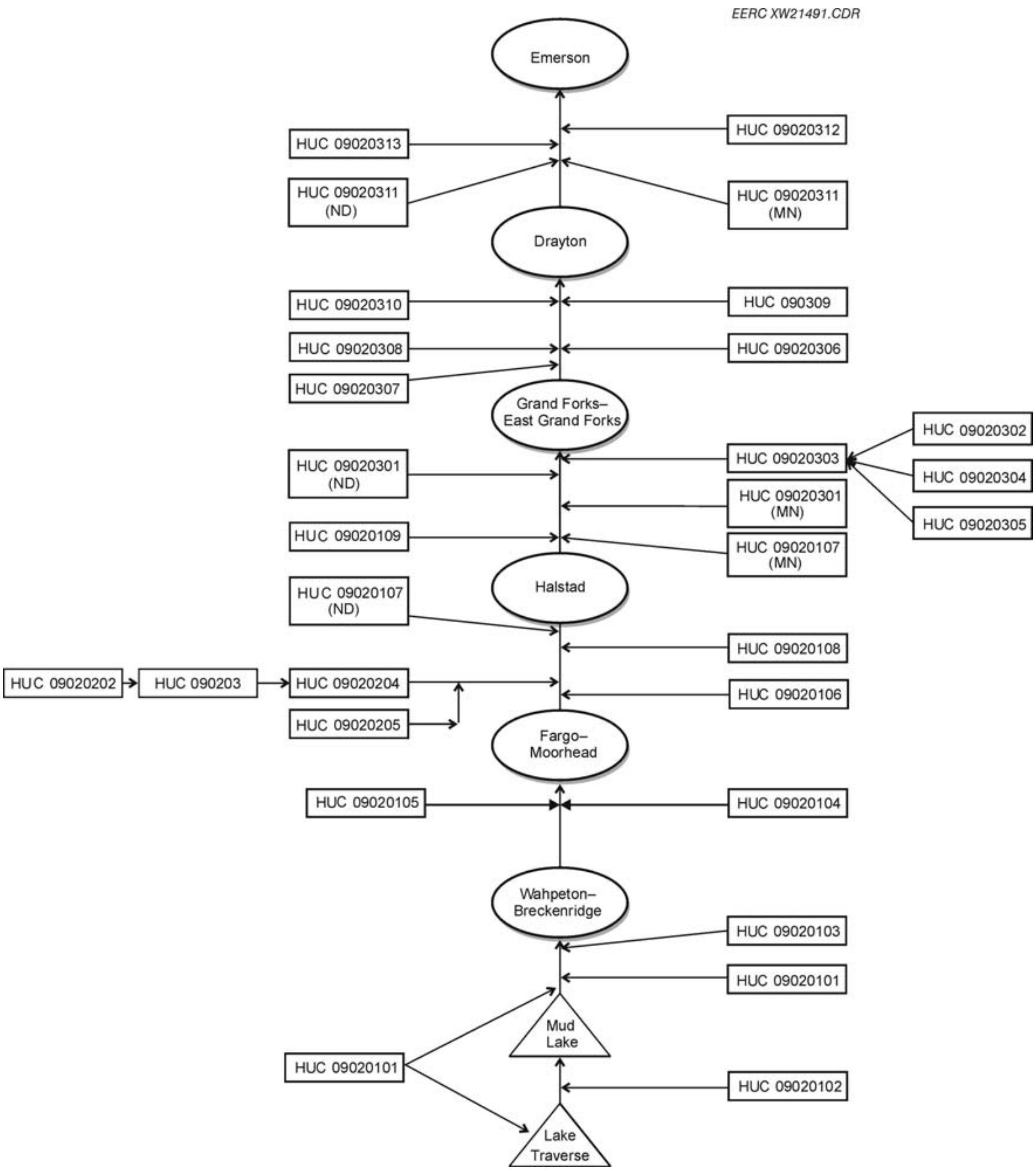


Figure 21. Hydraulic connectivity of the HUCs that comprise the RRB.

Table 5. The HUCs Comprising the RRB

No.	HUC	Name	Drainage Area, mi^2	Administration Boundary
1	09020101	Bois de Sioux	1140	Minnesota, North Dakota
2	09020102	Mustinka	825	Minnesota
3	09020103	Otter Tail	1980	Minnesota
4	09020104	Upper Red	594	Minnesota, North Dakota
5	09020105	Western Wild Rice	2380	North Dakota
6	09020106	Buffalo	1150	Minnesota
7	09020107	Elm–Marsh	1150	Minnesota, North Dakota
8	09020108	Eastern Wild Rice	1670	Minnesota
9	09020109	Goose	1280	North Dakota
10	09020202	Upper Sheyenne	1940	North Dakota
11	09020203	Middle Sheyenne	2070	North Dakota
12	09020204	Lower Sheyenne	1640	North Dakota
13	09020205	Maple	1620	North Dakota
14	09020301	Sandhill–Wilson	1130	Minnesota, North Dakota
15	09020302	Red Lakes	2040	Minnesota
16	09020303	Red Lake	1450	Minnesota
17	09020304	Thief	994	Minnesota
18	09020305	Clearwater	1350	Minnesota
19	09020306	Grand Marais–Red	482	Minnesota, North Dakota
20	09020307	Turtle	714	North Dakota
21	09020308	Forest	875	North Dakota
22	09020309	Snake	953	Minnesota
23	09020310	Park	1080	North Dakota
24	09020311	Lower Red	1320	Minnesota, North Dakota
25	09020312	Two Rivers	958	Minnesota
26	09020313	Pembina	2020	North Dakota
27	09020314	Roseau	1230	Minnesota

impoundments or nonstructural measures such as adaptation of conservative agricultural practices, wetland restoration, creation of riparian zones, and the use of existing temporary storage areas (De Laney, 1995; Napier et al., 1995). Using this approach and the models developed through this project, any combination of structural and/or nonstructural options throughout the RRB could be evaluated to determine flow reductions along the Red River and its tributaries and corresponding stage reductions along the Red River. Although the conceptual modeling scheme utilizes SWAT and HEC–RAS, any hydrologic and/or hydrodynamic model pairing could be utilized, such as SWAT and MIKE-11.

2.4.3 Description of SWAT

SWAT is a hydrologic model developed by the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS). It uses the physical characteristics of the landscape, such as soils, weather, land use, and topography, to predict the impact of land management practices on water, sediment and agricultural chemical yields in watersheds over long periods of time (Neitsch et al., 2002a, b). SWAT was developed in the early 1990s to help water resource managers assess the impact of management and climate on water supplies and non-point source pollution in small to large watersheds. Developed to “scale up” past field-scale models to large river basins, SWAT encompasses over 30 years of model development within ARS. SWAT is integrated with GIS, groundwater models, and policy tools to evaluate alternative management scenarios and impact analysis of various existing and proposed natural resource management practices.

SWAT comprises two main components, namely the land phase and the routing phase. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient, and pesticide loadings to the main channel in each subbasin based on landscape characteristics (topography, land use, land cover, soil type, etc.) and weather conditions (Neitsch et al., 2002a). The second component, the water or routing phase, determines how water, sediment, and chemical constituents will be routed through the channel network to the watershed outlet (Neitsch et al., 2002c). Both the land phase and routing phase contain several subcomponents. For example, the land phase component consists of eight subcomponents, namely hydrology, weather, sedimentation, soil moisture, crop growth, nutrients, agricultural management, and pesticides. In turn, each of these subcomponents takes into account additional processes. For example, the hydrology subcomponent uses local climatic data to determine precipitation, evaporation, transpiration from vegetation, soil temperature, snow accumulation and melt, overland runoff, recharge to the subsurface, and surface water discharge (Figure 22). A detailed description of the SWAT model and its functions can be found on Texas A&M's SWAT Web site (www.brc.tamus.edu/swat/index.html).

At the beginning of the Waffle study, there were hydrologic models available for several Minnesota watersheds that were developed using HEC–Hydrologic Modeling System (HMS). While the EERC initially considered using these models rather than developing new models using SWAT, the decision ultimately was to develop new models. The EERC's rationale for this is worth mentioning:

- While HEC–HMS needs fewer data and has been widely used to study water quantity, SWAT can be utilized to address a wider range of issues from water quantity to water quality.

- Although the hydrologic component of both models is comparable, SWAT has several advantages for flood reduction studies in the RRB. SWAT incorporates hydrologic response units (HRUs), portions of a subwatershed that possess unique land use–land management–soil attributes, which more accurately reflect the hydrologic characteristics of a study watershed. HRUs also allow for quantification of the hydrologic response of a particular landscape to changes in agricultural or land management practices.

- SWAT has a more comprehensive function for simulating small ponds and wetlands, which includes processes such as infiltration and evaporation. These components are well-suited for evaluating the Waffle concept and would allow Waffle storage areas to be simulated as either ponds or intermittent wetlands. On the other hand, HEC–HMS has been traditionally used to simulate big dams.

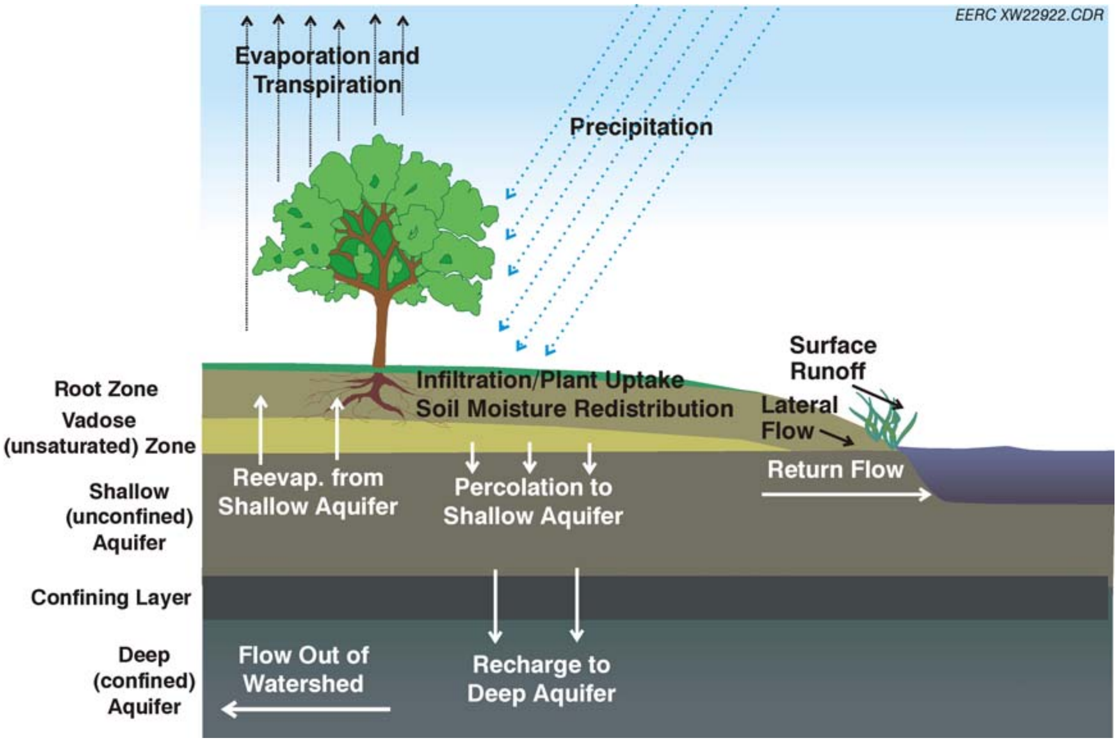


Figure 22. Key processes considered in the hydrology component of SWAT (Neitsch et al., 2002a).

- SWAT simulates runoff produced both by rainfall and snowfall in one run. Its snowfall component simulates snow accumulation and snow thaw, which is very convenient when studying the snowmelt-dominated flooding in the RRB. Conversely, when using HEC–HMS, a separate snow model is needed to convert the snowfall to the equivalent rainfall hyetographs needed for input (Shutov, 2000; Socolofsky et al., 2001).

- SWAT subdivides the vadose zone into several sublayers. The soil moisture and permeability affecting the infiltration into the vadose zone may be specified for each of the layers to more accurately consider antecedent conditions, one of the five constant factors leading to a casual flood (Bluemle, 1997). The recharge from the vadose zone into groundwater may be accurately simulated by the SWAT model.

- SWAT includes a water quality component. In addition to water yield, SWAT can simulate sediment and chemical loading, as well as crop yields corresponding to various weather conditions and alternative agricultural practices.

- SWAT has been seamlessly integrated with the databases developed and maintained by several federal agencies, including USGS, USDA, and the U.S. Environmental Protection Agency (EPA), which will undoubtedly expedite model development, standardization, usage, and upgrading. For example, the model parameters initially used can be automatically extracted from these databases and then adjusted for the study watershed to develop a calibrated and verified model.

A more detailed description of the SWAT model can be found in Appendix C.

2.4.4 SWAT Model Development

2.4.4.1 Data Quality and Availability

The basic inputs into the SWAT model included the 30-m USGS NED, the EPA 1:250,000-scale Land Use Land Cover (LULC) data set, and the USDA NRCS State Soil Geographic database (STATSGO). The LULC data set was developed by combining the data obtained from 1970s and 1980s aerial photography surveys with land use maps and surveys. Because there have been negligible changes in the types of RRB land use in the past two decades, as indicated by a comparison of the LULC and National Land Cover Dataset that was created by USGS from the 1992 aerial photography surveys, the LULC was an appropriate choice. Soil data contained within the STATSGO database are collected at the 1:250,000 scale in 1- by 2-degree topographic quadrangle units and then merged and distributed as state coverages. STATSGO has a county-level resolution and can be readily used for river basin water resource studies. The NED and LULC data sets were downloaded from the USGS Web site (http://edc.usgs.gove/geodata), and the STATSGO database was downloaded from the USDA NRCS Web site (www.ncgc.nrcs. usda.gov/branch /ssb/products). In addition to these three data sets, the USGS National Hydrography Dataset (NHD) was also used as a model input. The NHD is a comprehensive set of digital spatial data that contains information about surface water features such as lakes, ponds, streams, rivers, springs, and wells. The stream feature provided by NHD was utilized as the reference surface water drainage network to delineate subbasins for each of the USGS 8-digit HUCs for modeling purposes.

The National Weather Service (NWS) National Climate Data Center (NCDC) collects data on daily precipitation and minimum and maximum temperatures at stations across the RRB. Because the models were calibrated to the 1997 flood and validated against the 1966, 1969, 1975, 1978, and 1979 floods, weather data were utilized for these years. To minimize modeling uncertainties, the stations that had 30% or more values missing between October 1 and May 31 during these years were not used in this modeling effort. In addition to weather data, daily flow data obtained from USGS gauging stations for the aforementioned flood years were used to calibrate and validate the models. Figure 23 shows the locations of the NWS precipitation and temperature stations and the USGS flow-gauging stations that were used in this study. More detailed information describing the location and/or location name of the stations used in this study can be found in Tables C-2 and C-3 of Appendix C.

2.4.4.2 Calibration and Validation Strategy

The SWAT models were calibrated to the 1997 spring flood event using daily flow data observed from January 1 to May 31, 1997. In some instances, additional validation of the models was conducted using flow data recorded from January 1 to May 31 of 1966, 1969, 1975, 1978, and 1979. In the few cases where flow data were not available for a particular watershed, the SWAT models were set up based on scientific judgment, spot values observed by local engineers, and/or calibrated model parameters in the adjacent watersheds.

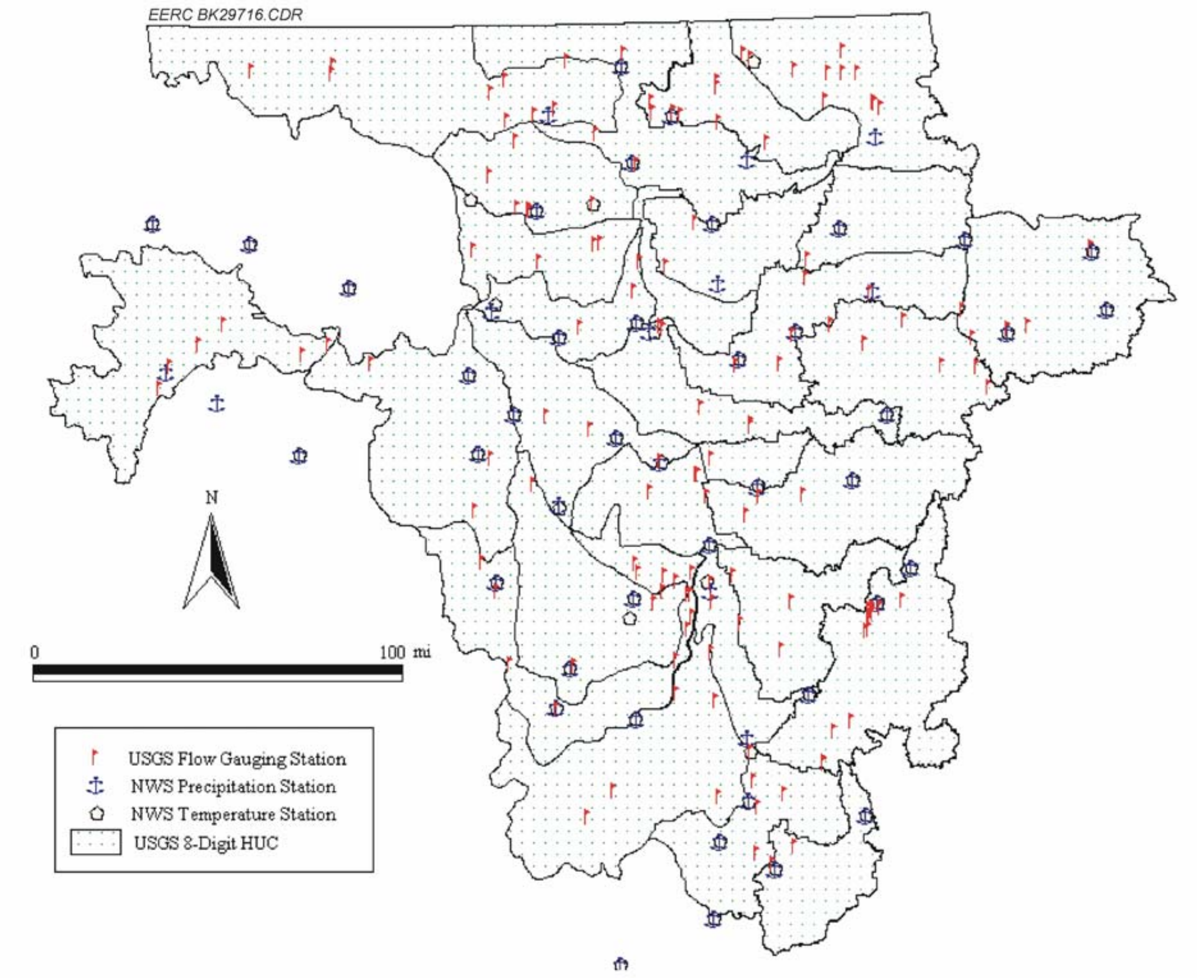


Figure 23. Map showing the locations of the weather stations and flow gauges used in this study.

One of the key qualitative measures of model performance is how well simulated flow hydrographs match the shape, volume, and peak of observed hydrographs for given locations within a watershed; however, to quantify the model performance, statistics are typically used. In this study, three statistics, namely the Nash-Sutcliffe coefficient, volume deviation, and error function, were used to determine model performance. These statistics can be applied for daily, monthly, seasonal, and annual evaluation time steps. The Nash-Sutcliffe coefficient measures the overall fit of the modeled hydrograph to that of an observed flow hydrograph. Nash-Sutcliffe coefficient values can range from $-\infty$ to 1.0, with higher values indicating a better overall fit and 1.0 indicating a perfect fit. A negative value indicates that for that location the simulated stream flows are less reliable than if one had used the average of the observed stream flows, while a positive value indicates that the simulated flows are more reliable than using this average. While there are no established guidelines indicating what Nash-Sutcliffe values are acceptable for model calibration, values of calibrated models reported in literature are typically greater than 0.36.

The accuracy of the models in predicting the measured flood volume is quantified through the deviation in volume. The values for this statistical parameter can range from very small negative to very large positive values, with values close to zero indicating a better simulation and zero indicating an exact prediction of the observed volume.

The last statistical measure used to evaluate model performance was the error function, which measures how accurately the model predicts the timing and magnitude of the flood peak. In contrast with the Nash-Sutcliffe coefficient, error function values can range from 0.0 to $+\infty$, with lower values indicating a better simulation of the observed peak and 0.0 indicating that both the magnitude and timing of the observed peak can be exactly predicted by the model.

The performance of the SWAT models according to the above criteria is summarized in Table 6. The performance of the SWAT models for individual watersheds can be found in Appendix C. The Roseau River Watershed in Minnesota and the Middle Sheyenne River Watershed in North Dakota performed considerably worse than the other watershed models in terms of deviation in volume and error function. In each case, this may be a result of the lack of data regarding the location of wetlands and marshes. However, these models were not used to evaluate Waffle storage because the Roseau River flows into the Red River downstream of the U.S. border, and the flow at the outlet of the Middle Sheyenne Watershed is controlled by Baldhill Dam. Thus the statistics were also calculated without including the values for these watersheds. Those values are also listed in Table 6. Overall, the models performed well and were judged to be accurate enough for evaluating the effects of Waffle storage on reducing 1997-type floods.

2.4.5 Modeled Flow Reductions in the RRB Watersheds

For each watershed listed in Table 5, three Waffle storage scenarios were generated and evaluated to determine peak flow reductions at the outlets of each tributary and, in some cases, in upstream reaches of the tributaries. Each of these storage scenarios was based on the EERC's

Table 6. Summary of the Statistics Used to Evaluate SWAT Model Performance

	Nash-Sutcliffe Coefficient	Deviation in Volume	Error Function
Average for Minnesota SWAT Models	0.61	3.4	13.2
Range for Minnesota SWAT Models	0.27 to 0.86	−27.2 to 32.5	1.1 to 60.7
Average for Minnesota SWAT Models, Excluding Roseau River	0.60	0.6	7.8
Range for Minnesota SWAT Models, Excluding Roseau River	0.27 to 0.86	−27.2 to 32.5	1.1 to 16.7
Average for North Dakota SWAT Models	0.66	-8.9	22.9
Range for North Dakota SWAT Models	0.18 to 0.9	−66.3 to 12.7	10 to 65.7
Average for North Dakota SWAT Models, Excluding Middle Sheyenne River	0.69	−3.1	18.6
Range for North Dakota SWAT Models, Excluding Middle Sheyenne River	0.18 to 0.9	−20.3 to 12.7	10 to 31.9

most conservative storage estimate, corresponding to a total volume of approximately 583,400 acre-ft. Scenario I (S-I) modeled 100% of the conservative Waffle storage volume, whereas, Scenario II (S-II) and Scenario III (S-III) evaluated 75% and 50% of the conservative storage volume, respectively. This was done to estimate the flood reduction effects if only a certain percentage of Waffle storage was utilized during a flood event like 1997. To obtain the storage volumes that are 75% and 50% of the original estimates, Waffle storage areas in each watershed were randomly eliminated by 25% and 50%, respectively, and the total storage volume was recalculated.

Table 7 lists the three Waffle storage volumes for each RRB watershed, except for HUC 09020202 (Upper Sheyenne), HUC 09020203 (Middle Sheyenne), HUC 09020302 (Red Lakes), and HUC 09020314 (Roseau). The runoff generated in HUC 09020202 (Upper Sheyenne) and HUC 09020203 (Middle Sheyenne) is regulated by the Baldhill Dam, which could offset the effects of Waffle storage on Red River flow and stage reductions. Similarly, the runoff generated in HUC 09020302 is regulated by the Red Lake Dam. The Roseau River (HUC 09020314) does

Table 7. Waffle Storage Volumes of the Three Analyzed Scenarios: Scenario I (S-I), Scenario II (S-II), and Scenario III (S-III). S-I considers 100% of the Conservative Storage Estimate, Whereas, S-II and S-III evaluate 75% and 50% of the conservative storage estimate, respectively

State	Modeling Domain	Watershed	S-I, ac-ft	S-II, ac-ft	S-III, ac-ft
MN	HUC 09020101	Rabbit	22,800	17,200	13,300
	HUC 09020102	Mustinka	6500	5200	3200
	HUC 09020103	Otter Tail	2400	1700	900
	HUC 09020104	Upper Red	38,900	29,400	16,700
	HUC 09020106	Buffalo	21,500	16,300	10,300
	HUC 09020107	Marsh	35,000	27,300	16,100
	HUC 09020108	Wild Rice MN	20,300	15,100	10,300
	HUC 09020301	Sandhill	16,300	12,800	9500
	HUC 09020303	Red Lake	60,700	46,900	31,600
	HUC 09020306	Grand Marais	25,200	18,800	12,400
	HUC 09020309	Snake	12,500	9200	5700
	HUC 09020311	Lower Red	36,100	27,400	16,100
	HUC 09020312	Two Rivers	18,500	14,600	8800
ND	HUC 09020101	Bois de Sioux	3300	2800	1800
	HUC 09020105	Wild Rice	27,000	21,000	13,100
	HUC 09020107	Elm	32,700	24,700	16,600
	HUC 09020109	Goose	20,400	14,600	11,300
	HUC 09020204	Lower Sheyenne	27,200	19,300	12,900
	HUC 09020205	Maple	14,200	10,400	7000
	HUC 09020301	Wilson	19,700	14,700	9800
	HUC 09020307	Turtle	5300	4100	3100
	HUC 09020308	Forest	5600	4600	2800
	HUC 09020310	Park	26,100	20,400	12,400
	HUC 09020311	Lower Red	16,000	12,600	7800
	HUC 09020313	Pembina	9200	7400	5100
Total			523,400	398,500	258,600

not directly contribute runoff to the Red River in the United States. Thus Waffle storage areas for these four modeling domains were not modeled and are not shown in Table 7. In addition, the Waffle storage volume listed in Table 7 for the Red Lake River Watershed (HUC 09020303) also includes the storage volumes from Thief and Clearwater River Watersheds (HUC 09020304 and 09020305). Details on the identification of potential Waffle storage areas across the RRB are documented in Section 2.3 of this report.

Readers should be aware that the volumes listed in Table 7 for 100% of identified Waffle storage are somewhat different than the values presented in Section 2.3 of this report. This discrepancy is the result of two main reasons. First, in Section 2.3, the storage areas are summarized in terms of the USGS 8-digit HUCs provided by NHD, whereas, the corresponding values in Table 7 were reported in terms of the individual watersheds delineated by SWAT using the 30-m NED data. It is important to remember that those watersheds with drainage areas on both sides of the Red River (i.e., Elm-Marsh) were divided into two separate SWAT models based on their respective North Dakota and Minnesota components. Although efforts were made to make the delineated boundaries closely match the corresponding ones provided by the NHD, a close examination indicated that these boundaries could be offset by as much as 10%. This small offset is considered acceptable given the coarse resolution of, and inherent errors in, the NED data. Second, the USGS 8-digit HUCs that cover both Minnesota and North Dakota, including the Bois de Sioux (09020101), Upper Red (09020104), Elm-Marsh (09020107), Sandhill-Wilson (09020301), and Lower Red (092020311) Watersheds, were split into two modeling domains, which lost 5% to 10% of the drainage areas adjacent to the Red River because of the coarse NED resolution. As a result, the modeled Waffle storage areas and volumes are less than the values originally identified in Section 2.3, which would make the analyzed Waffle effects on flood reduction more conservative.

The Waffle effects were measured by comparison of peak flow reductions as a result of Waffle storage (post-Waffle conditions) to peak flows without Waffle storage (pre-Waffle conditions) at the outlet of, and at key points within, each modeled watershed. The percent reduction in peak flow was calculated by:

$$\text{Effect} = \frac{(\text{post-Waffle peak}) - (\text{pre-Waffle peak})}{(\text{pre-Waffle peak})} \times 100\% \qquad \text{[Eq. 5]}$$

For each watershed, the evaluation of three Waffle storage scenarios (100%, 75%, and 50%) was conducted to determine the flow reductions at the mouths of each tributary during a 1997-type flood. These results are presented in the following section. Because time permitted, additional efforts were also conducted to evaluate the Waffle effect for five additional flood events (1966, 1969, 1975, 1978, 1979) at various points within the Minnesota watersheds. These results are presented in Appendix C.

2.4.6 Modeling Results and Discussion

For a 1997-type flood, S-I was predicted to result in a reduction of peak flows at outlets of the modeling domains by 0.3% to 59.2%, whereas, S-II and S-III would reduce the peaks by 0.3% to 45.2% and 0.0% to 27.2%, respectively (Table 8 and Figures 24 and 25). The percent reduction is larger overall for watersheds with a greater south–north width than for those with a greater east–west length. For example, the Upper Red River Watershed (modeling domain HUC 09020104) has a south–north width much greater than its east–west length and was predicted to have a reduction of 59.2%. The Lower Sheyenne River Watershed (modeling domain HUC 09020204), on the other hand, has a south–north width much smaller than its east–west length and was predicted to have a reduction of only 1.4%. One explanation for this may be that the dominant drainage area of a watershed with a larger width-to-length ratio is adjacent to the watershed outlet. As a result, the flow reductions exhibited as a result of Waffle storage can be achieved without much dissipation in the effects of storage. In contrast, the Waffle effect for a watershed with a smaller width-to-length ratio tends to dissipate significantly before the effect can be noticed at the watershed outlet. Another explanation is that a watershed with a greater width-to-length ratio tends to be dominated by overland processes rather than channel processes; that is, in general, precipitation has a longer travel time on the land than along the associated streams. Thus overland runoff has a greater chance to be intercepted and regulated by the Waffle storage areas before it becomes concentrated stream flows. Because the Waffle storage areas are scattered across the watershed and an individual Waffle storage area (i.e., a section) usually has limited storage capacity, the effect of the storage areas on handling the concentrated stream flows is much lower than that on regulating the corresponding overland runoff. This indicates that cumulative effects of Waffle storage areas offer more overall benefit than any one individual storage area.

As expected, watersheds with more Waffle storage areas experienced larger flow reductions. For all watersheds, S-I was predicted to have a greater effect than S-II which, in turn, was predicted to have larger effects than S-III (Table 8). The average difference in effect between two consecutive scenarios (i.e., S-I versus S-II and S-II versus S-III) was determined to be approximately 3.2%. The watersheds with smaller drainage areas and/or greater width-to-length ratios are more sensitive to changes in Waffle storage areas. For example, in the Marsh River Watershed, the reduction difference between consecutive storage scenarios was about 10.5%, whereas, in modeling domain HUC 09020303 (includes the Red Lake, Clearwater, and Thief River Watersheds), which has a much larger drainage area of 3533 mi^2, the reduction difference was only 1%. This is an indication that the Waffle may be more effective in controlling overland runoff than concentrated stream flows. Compared with conventional reservoirs, which are usually situated on drainage channels and intercept all upstream stream flows, the Waffle reduces flood peaks as a result of the cumulative effects of individual, small storage areas.

Table 8. Effects on Reducing 1997-Type Peaks as Measured at the Outlets of the Modeling Domains for the Three Waffle Scenarios

State	Modeling Domain	Watershed	Pre-Waffle Peak, cfs	Scenario I (S-I)		Scenario II (S-II)		Scenario III (S-III)	
				Peak, cfs	Effect, %	Peak, cfs	Effect, %	Peak, cfs	Effect, %
MN	HUC 09020101	Rabbit	6185	5000	19.2	5320	14.0	5458	11.8
	HUC 09020102	Mustinka	9915	9735	1.8	9780	1.4	9830	0.9
	HUC 09020103	Otter Tail	1615	1610	0.3	1610	0.3	1615	0.0
	HUC 09020104	Upper Red	1250	510	59.2	685	45.2	910	27.2
	HUC 09020106	Buffalo	8700	8575	1.4	8610	1.0	8640	0.7
	HUC 09020107	Marsh	7910	5540	30.0	6385	19.3	7215	8.8
	HUC 09020108	Wild Rice MN	10,735	10,095	6.0	10,255	4.5	10,405	3.1
	HUC 09020301	Sandhill	4515	4015	11.1	4100	9.2	4250	5.9
	HUC 09020303	Red Lake	20,070	19,090	4.9	19,270	4.0	19,540	2.6
	HUC 09020306	Grand Marais	680	385	43.4	450	33.8	500	26.5
	HUC 09020309	Snake	14,480	13,835	4.5	13,995	3.3	14,175	2.1
	HUC 09020311	Lower Red	3890	3190	18.0	3360	13.6	3480	10.5
	HUC 09020312	Two Rivers	4775	4100	14.1	4230	11.4	4445	6.9
ND	HUC 09020101	Bois de Sioux	2428	2080	14.3	2084	14.2	2090	13.9
	HUC 09020105	Wild Rice	8529	8084	5.2	8264	3.1	8296	2.7
	HUC 09020107	Elm	4885	3460	29.2	3760	23.0	4120	15.7
	HUC 09020109	Goose	7695	7430	3.4	7508	2.4	7554	1.8
	HUC 09020204	Lower Sheyenne	4775	4708	1.4	4729	1.0	4747	0.6
	HUC 09020205	Maple	6586	6488	1.5	6516	1.1	6537	0.7
	HUC 09020301	Wilson	5745	4780	16.8	5135	10.6	5477	4.7
	HUC 09020307	Turtle	2265	2168	4.3	2188	3.4	2207	2.6
	HUC 09020308	Forest	2956	2768	6.4	2826	4.4	2906	1.7
	HUC 09020310	Park	7374	6286	14.7	6724	8.8	7335	0.5
	HUC 09020311	Lower Red	3456	2770	19.8	2878	16.7	2999	13.2
	HUC 09020313	Pembina	19,205	18,680	2.7	18,774	2.2	18,929	1.4
Average			6825	6215	13.3	6377	10.1	6546	6.7

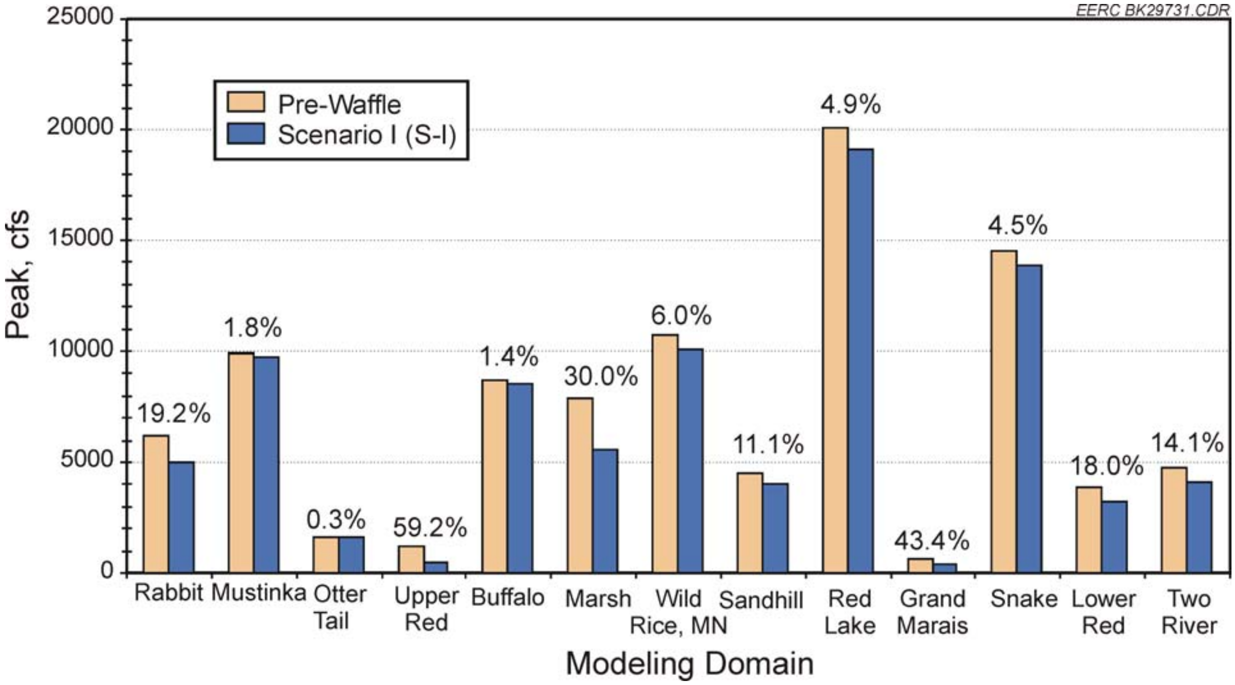


Figure 24. Plot showing the predicted reductions in 1997-type flood peaks at the outlets of Minnesota modeling domains as a result of implementing Waffle Scenario I.

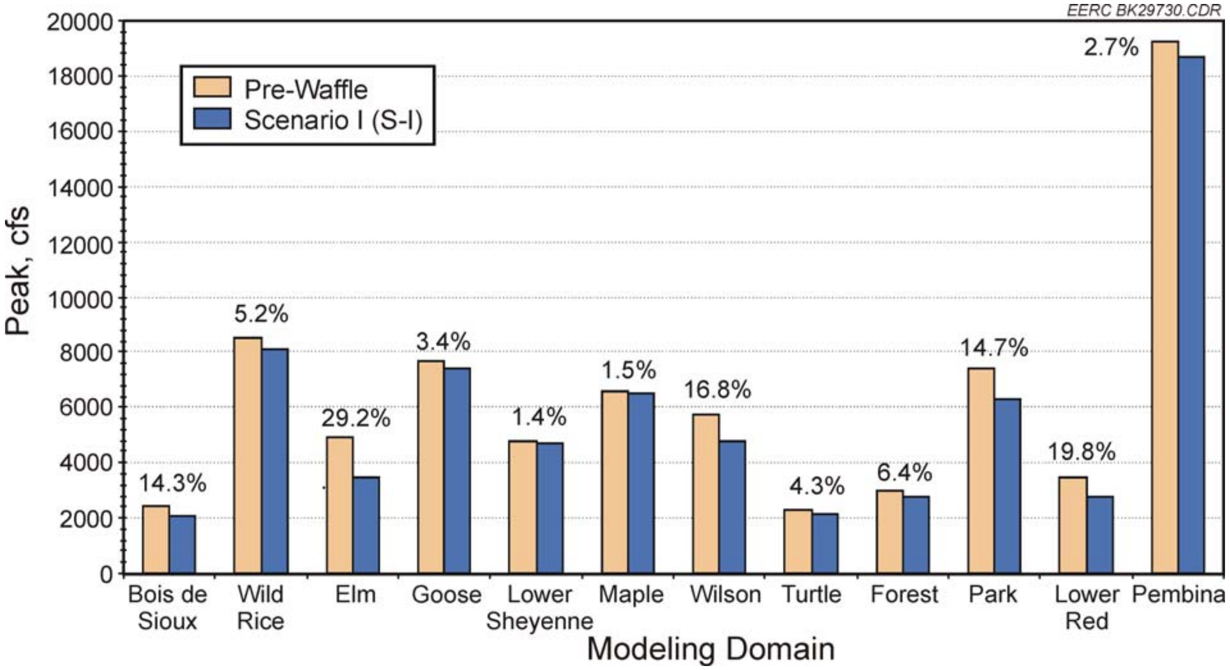


Figure 25. Plot showing the predicted reductions in 1997-type flood peaks at the outlets of North Dakota modeling domains as a result of implementing Waffle Scenario I.

The spatial distribution of the Waffle storage areas within a watershed (modeling domain) is also important for flood reduction. For S-I, the Rabbit and Buffalo River Watersheds were identified to have near-equivalent Waffle storage volumes (22,783.87 acre-ft versus 21,495.07 acre-ft; Table 7). However, the spatial locations of the storage areas within each watershed are distinctly different (Figure 26). In the Buffalo River Watershed, the Waffle storage areas are primarily located in the lower portion, where the hydrologic processes were dominated by concentrated stream flows. As a result, Waffle storage has a very limited effect, as indicated by the small percent reduction of 1.4% for the peak at the watershed outlet. In contrast, the Waffle storage areas in the Rabbit River Watershed cover most of the upland areas that have hydrologic processes primarily dominated by overland runoff. This spatial distribution is ideal for achieving flood reduction using the Waffle concept, as indicated by the large percentage reduction of 19.2% for the peak at the watershed outlet. The importance of the spatial distribution of the Waffle storage areas on flood reduction for a watershed was further verified by examining the percent reductions in peak flows at several points of interest within the Minnesota watersheds. This is discussed in more detail in Appendix C.

2.4.7 HEC–RAS Modeling

Once the evaluation of the Waffle storage effects in the watersheds of the RRB was completed, the next step was to determine how the peak flow reductions in the tributaries translated to flow and stage reductions along the Red River. To accomplish this, a hydrodynamic HEC–RAS model was constructed. HEC–RAS is a computer software program designed to model the flow of water through natural river systems as well as constructed channels. The program was developed by USACE through the HEC for use in managing rivers, harbors, and other public works under their jurisdiction. The current version of HEC–RAS supports steady and unsteady flow water surface profile calculations. The hydraulic calculations for cross sections, bridges, culverts, and other hydraulic structures that were developed for the steady flow component were incorporated into the unsteady flow module. The unsteady flow module has the ability to model storage areas and hydraulic connections between storage areas as well as between stream reaches. However, this module was developed primarily for subcritical flow regime calculations.

In this study, two HEC–RAS hydrodynamic (unsteady-state) models were used to predict reductions of the 1997 flood crests along the Red River main stem. The first model, developed by the USACE St. Paul District, covers the reach from White Rock to Halstad. The second model, developed by the EERC, includes the reach from Halstad to Emerson. The outputs from the first model were used as the inputs into the second model, enabling a seamless prediction along the main stem from White Rock to Emerson. For description purposes, hereinafter, the first model is designated "ACE-M," whereas the second model is designated "EERC-M." The common features of these two models are that 1) the flows simulated by the aforementioned SWAT models were used to define the boundary conditions when the USGS-observed data were unavailable; 2) the flows from the ungauged drainage areas (i.e., areas that contribute flow that is not measured by any USGS gauging station) were simulated by the SWAT models; 3) the major tributaries were explicitly modeled; 4) all bridges and major breakout flows, such as that which occurred along the Maple and Sheyenne Rivers and at the Thompson Bridge, were considered;

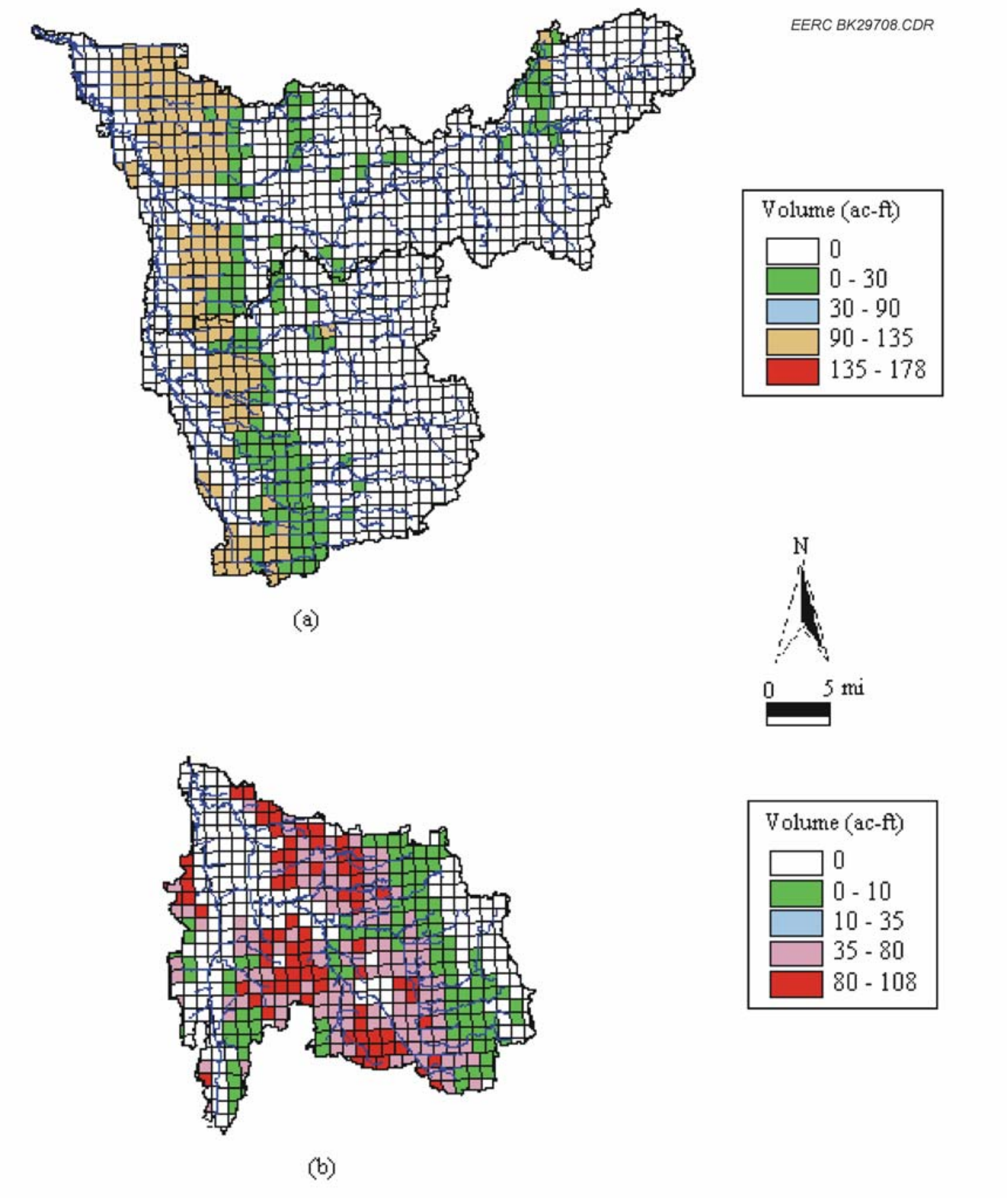


Figure 26. Map showing the spatial distribution of the Waffle Scenario I storage areas within the a) Buffalo River Watershed and b) Rabbit River Watershed.

5) all available cross-sectional data for the main stem Red River were used; and 6) the models incorporated the best knowledge of local and regional engineers, including Mr. James Fay (North Dakota State Water Commission); Mr. Stuart Dobberpuhl (USACE); Mr. Michael Lesher (USACE), Mr. Dennis Reep (NRCS), Mr. Scott Jutila (USACE), and Mr. Randy Gjestvang (North Dakota State Water Commission), to name a few.

The geometric data for the cross sections and bridges along the Red River main stem were extracted from the HEC–RAS steady-state model that was distributed with the USACE's "Regional Red River Flood Assessment Report," dated January 2003. In addition, the cross sectional data for the tributaries that were modeled in ACE-M were generated using the USGS 1:24,000 quadrangles maps or extracted from a HEC–RAS unsteady-state model developed by Pacific International Engineering for the "Maple River and Overflow Area Flood Insurance Study." Details on ACE-M can be found in the final report for USACE's "Fargo–Moorhead Upstream Feasibility Study" project, entitled "Hydrology and Hydraulics Analysis." Additional details on EERC-M can be found in Appendix C.

Both HEC–RAS models were calibrated in accordance with the 1997 flood. A key goal of the calibration of EERC-M was to achieve a close match between the simulated water surface elevation hydrographs and the corresponding observed hydrographs at Halstad, Drayton, Pembina, and Emerson. However, because it is infeasible to have best matches for both flow and elevation, the first priority of the calibration was an accurate simulation of flows. The observed flow hydrograph at Grand Forks was not used for the model calibration because the Grand Forks–East Grand Forks Dike Project has noticeably changed the topography and geomorphology of the subreach located within the city limits. Given these changes, a hydrologic condition that is identical to that of 1997 would result in a distinctly different flow hydrograph. In order to evaluate the effects of proposed flood mitigation projects (i.e., the Waffle) on flood crest reductions, the geometric data for the current ground truth conditions (i.e., the topography with the dikes and diversions constructed) rather than the 1997 geomorphology was used to set up the model. The observed flow hydrographs at stations downstream of Grand Forks were used to calibrate the model because USACE has shown that the changes in the Grand Forks–East Grand Forks dike project have a negligible influence on the flow regimes located 1 mile away from the northern boundary of the project (Mike Lescher, personal communication, 2006).

As shown in Table 9, EERC-M performed well in predicting both peaks and volumes. As expected, Halstad is the model upper boundary, and thus the predicted and observed values at this station are identical. The model successfully reproduced the peak discharges and timings at the three stations downstream of Grand Forks. For those three stations, the maximum prediction error for timing is only off by 1.72%, or 1 day. In addition, the prediction error for volumes at those stations is less than 1%. The results for Grand Forks are presented for informational purposes only because this station was not used for model calibration. Nevertheless, the model performance is acceptable for Grand Forks as well. Further, the model predicted the daily discharge with sufficient accuracy, as indicated by R^2 values of 0.65 or greater and slopes nearing 1 (Figures 27–30). Also, the predicted stage hydrographs match well with the corresponding observed hydrographs (Figures 31–35). The observed stages were obtained from USACE. Again, the results for Grand Forks are shown for informational purposes only because this station was not used for model calibration.

Table 9. Observed and EERC-M Predicted Peaks and Volumes for the 1997 Flood

	Observed Peak		Predicted Peak		_Volume (from April 14 to May 10)		
Station	Magnitude, cfs	Timing	Magnitude, cfs	Timing	Observed, ac-ft	Predicted, ac-ft	Error, %
Halstad[1]	69,900	April 19	69,900	April 19	2,323,041	2,323,041	0.00
Grand Forks[2]	127,000	April 18	102,420	April 22	3,613,091	3,381,224	−6.42
Drayton	124,000	April 24	121,859	April 24	3,882,446	4,240,783	0.92
Pembina[3]	141,400	April 26	140,430	April 27	4,429,307	5,032,677	0.93
Emerson[4]	141,400	April 26	140,488	April 27	4,439,217	5,032,312	0.74

[1] As the model upper boundary, the predicted and observed values at this station are identical.

[2] The results are presented for informational purposes only because the station was not used for model calibration.

[3] The observed flow hydrograph was derived by Dr. Xixi Wang, P.E., a research scientist at the EERC, using the data on observed stages and the rating curve provided by Mr. Steven Robinson of USGS.

[4] The observed flow hydrograph was provided by Mr. Alf Warkentin from Manitoba Water Stewardship. This corrected hydrograph considered the overflows that occurred at the west bank of the Red River in the vicinity of Emerson. In contrast, the USGS data did not consider the overflows.

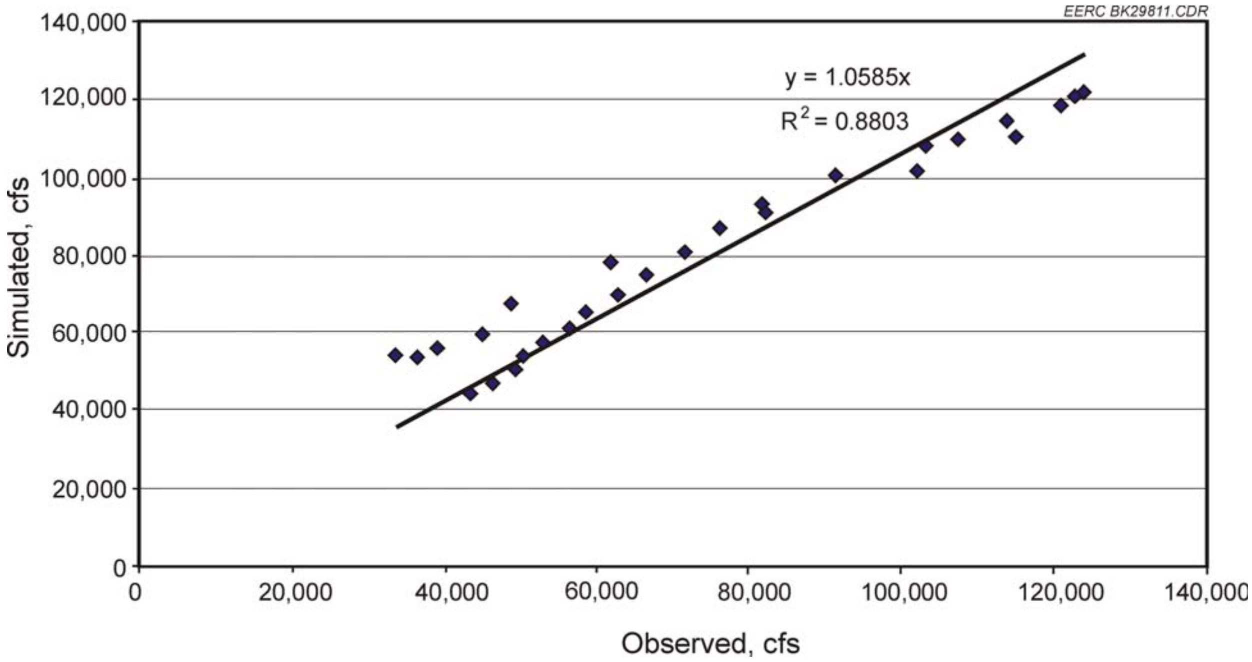


Figure 27. Plot of the simulated versus observed daily discharges at Drayton.

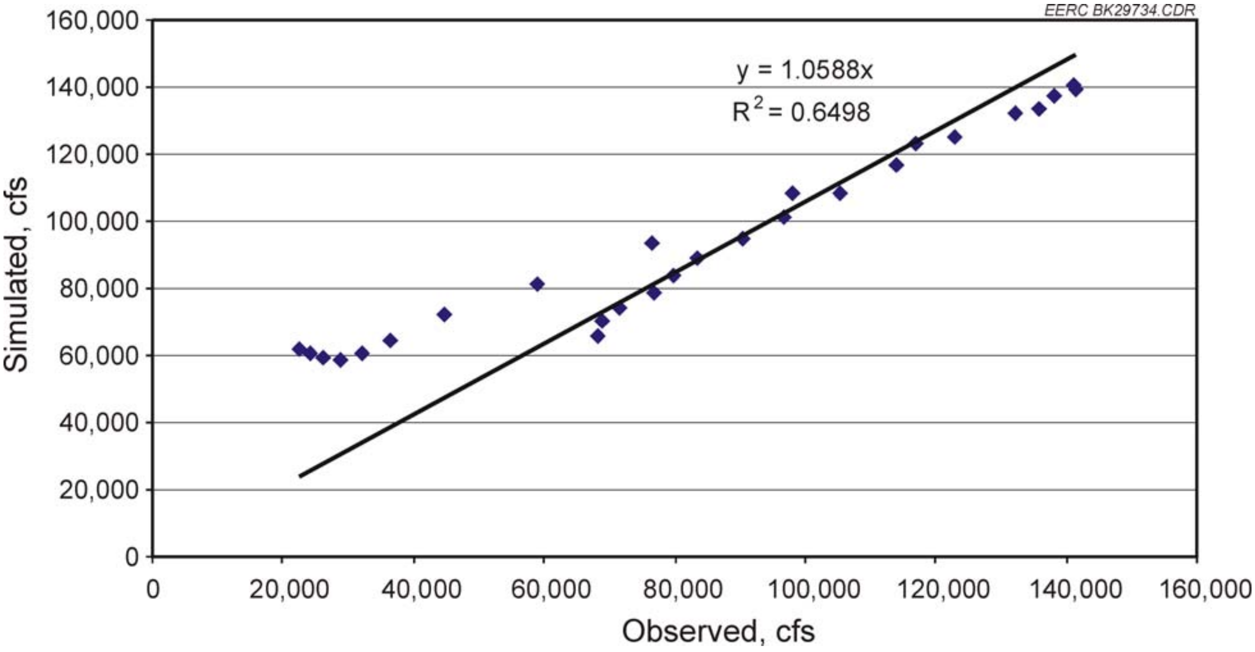


Figure 28. Plot of the simulated versus observed daily discharges at Pembina.

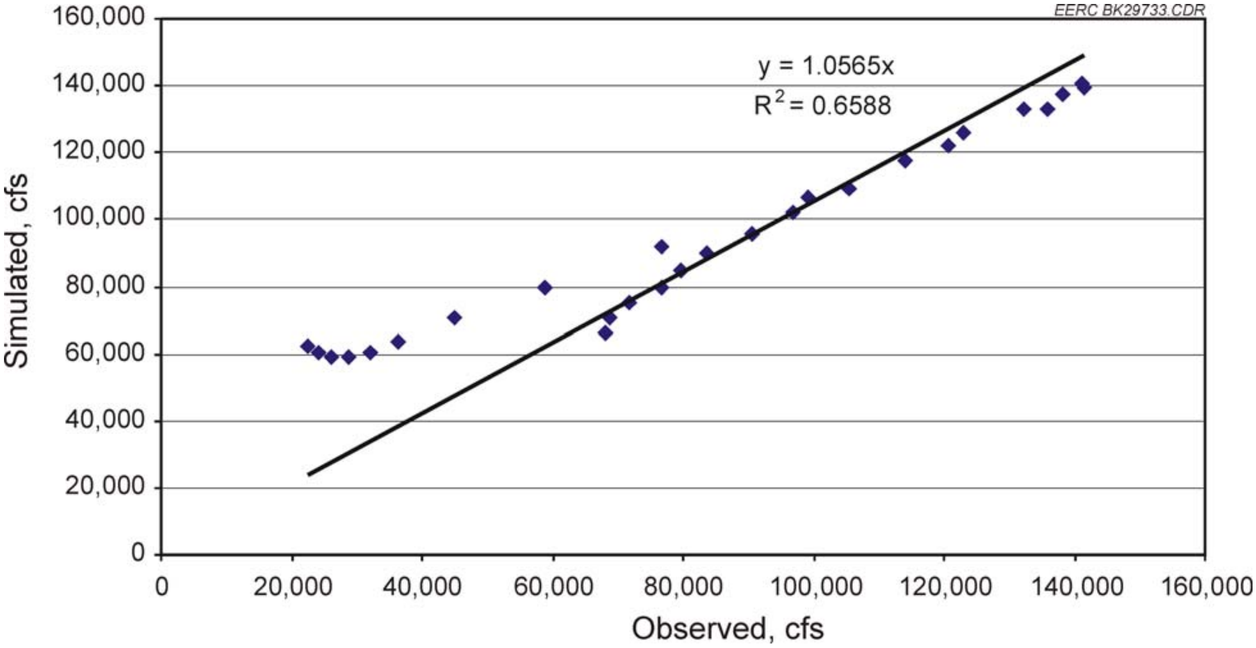


Figure 29. Plot of the simulated versus observed daily discharges at Emerson.

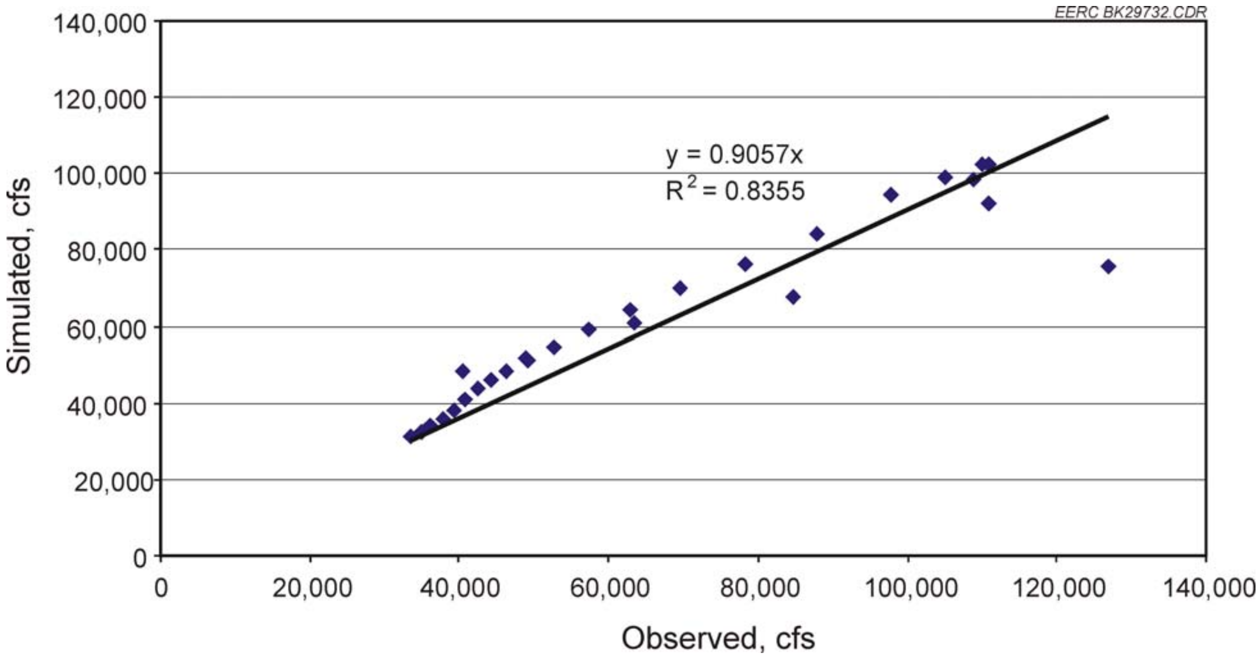
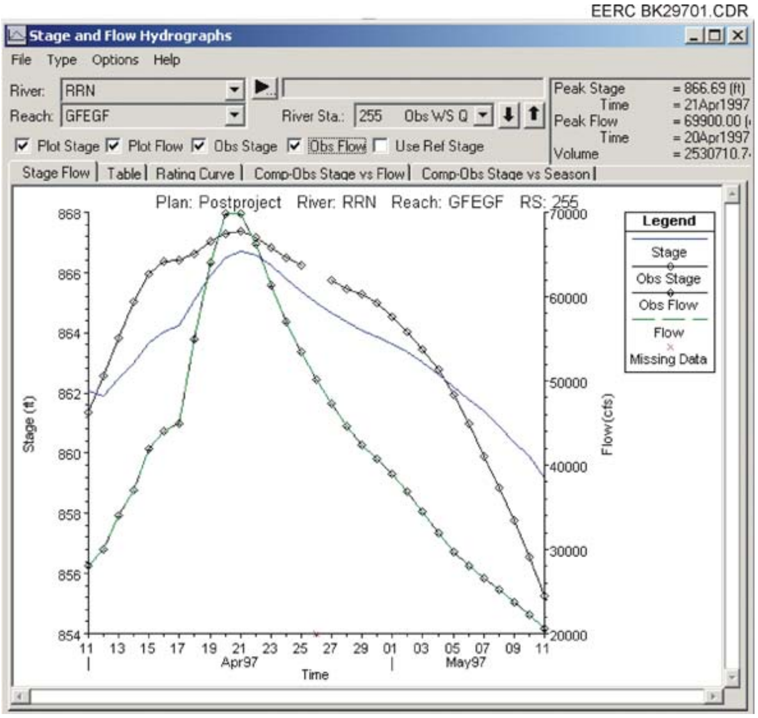


Figure 30. Plot of the simulated versus observed daily discharges at Grand Forks. Note that this station was not used for model calibration. The results are shown for informational purposes only.



River: RRN

Reach: GFEGF

River Sta.: 255 Obs WS Q

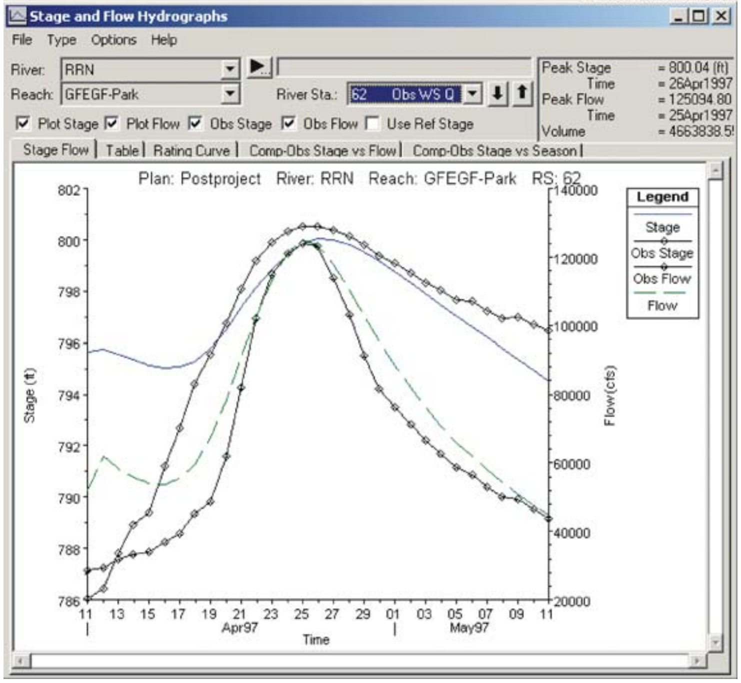
☑ Plot Stage ☑ Plot Flow ☑ Obs Stage ☑ Obs Flow ☐ Use Ref Stage

Peak Stage = 866.69 (ft)
Time = 21Apr1997
Peak Flow = 69900.00 (
Time = 20Apr1997
Volume = 2530710.7

Plan: Postproject River: RRN Reach: GFEGF RS: 255

Figure 31. Plot of the measured and model-predicted discharges (flows) and water surface elevations at Halstad.

EERC BK29702.CDR



River: RRN

Reach: GFEGF-Park

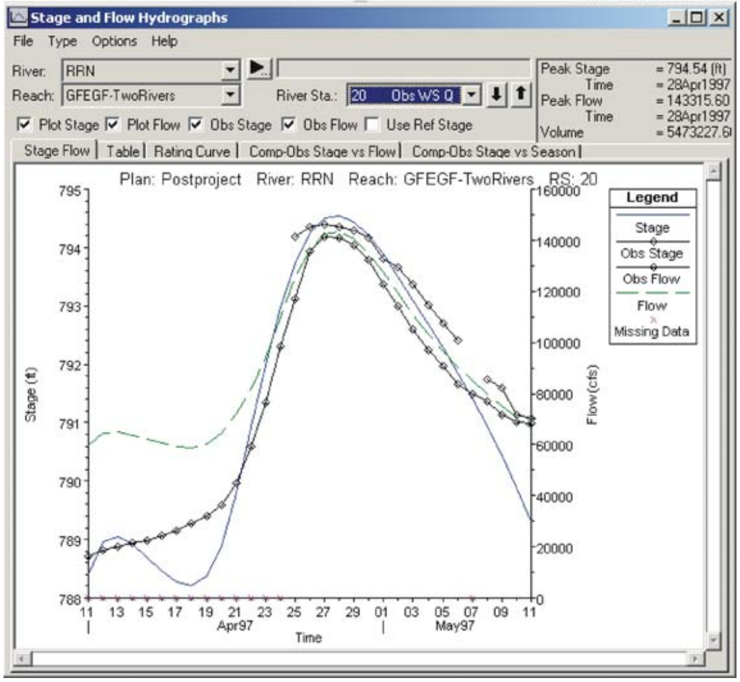
River Sta.: 62 Obs WS Q

☑ Plot Stage ☑ Plot Flow ☑ Obs Stage ☑ Obs Flow ☐ Use Ref Stage

Peak Stage = 800.04 (ft)
Time = 26Apr1997
Peak Flow = 125094.80
Time = 25Apr1997
Volume = 4663838.5

Figure 32. Plot showing the measured and model-predicted discharges (flows) and water surface elevations at Drayton.

EERC BK29703.CDR



River: RRN

Reach: GFEGF-TwoRivers

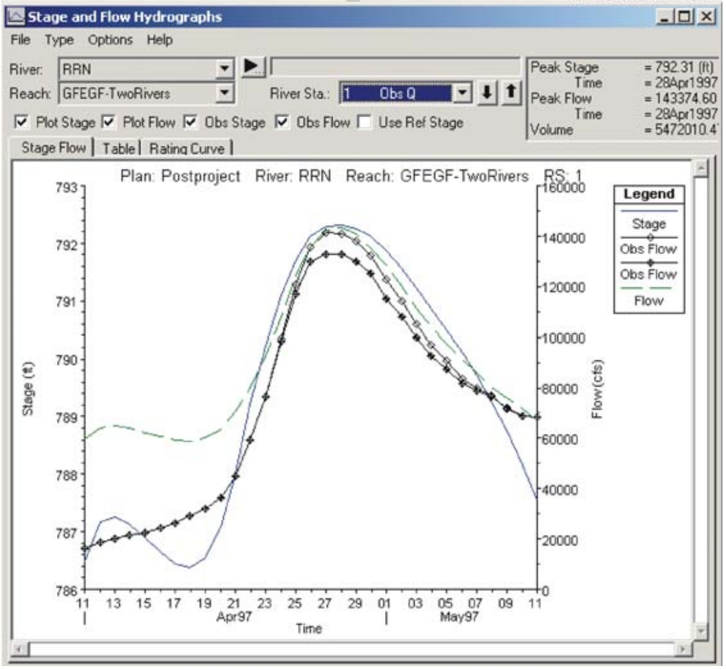
River Sta.: 20 Obs WS Q

☑ Plot Stage ☑ Plot Flow ☑ Obs Stage ☑ Obs Flow ☐ Use Ref Stage

Peak Stage = 794.54 (ft)
Time = 28Apr1997
Peak Flow = 143315.60
Time = 28Apr1997
Volume = 5473227.6

Figure 33. Plot showing the measured and model-predicted discharges (flows) and water surface elevations at Pembina.

EERC BK29704.CDR



River: RRN
Reach: GFEGF-TwoRivers
River Sta.: 1 Obs Q

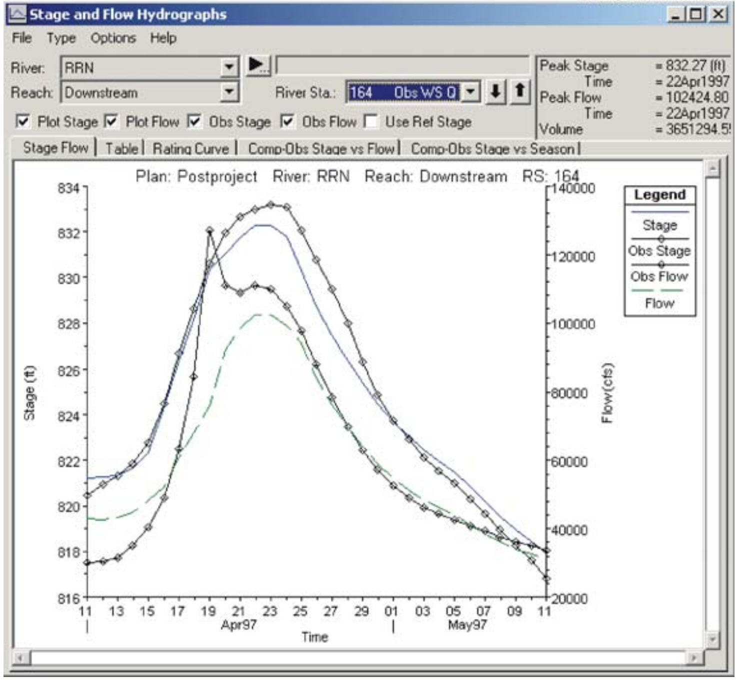
☑ Plot Stage ☑ Plot Flow ☑ Obs Stage ☑ Obs Flow ☐ Use Ref Stage

Peak Stage = 792.31 (ft)
Time = 28Apr1997
Peak Flow = 143374.60
Time = 28Apr1997
Volume = 5472010.4

Plan: Postproject River: RRN Reach: GFEGF-TwoRivers RS: 1

Figure 34. Plot showing the measured and model-predicted discharges (flows) and water surface elevations at Emerson.

EERC BK29705.CDR



River: RRN
Reach: Downstream
River Sta.: 164 Obs WS Q

☑ Plot Stage ☑ Plot Flow ☑ Obs Stage ☑ Obs Flow ☐ Use Ref Stage

Peak Stage = 832.27 (ft)
Time = 22Apr1997
Peak Flow = 102424.80
Time = 22Apr1997
Volume = 3651294.5

Plan: Postproject River: RRN Reach: Downstream RS: 164

Figure 35. Plot showing the measured and model-predicted discharges (flows) and water surface elevations at Grand Forks. Note that this station was not used for model calibration. The results are shown for information purposes only.

2.4.8 *Modeled Flood Crest Reductions Along the Main Stem*

Along the main stem, nine locations, namely Wahpeton, Hickson, Fargo, Halstad, Grand Forks, Oslo, Drayton, Pembina, and Emerson, were selected to examine the effects of the conservative Waffle storage volumes on reducing a 1997-type flood. The evaluation locations correspond to USGS gauging station locations. The observed daily stream flows were obtained from USGS and Manitoba Water Stewardship, whereas the observed water surface elevations were obtained from USACE.

As a result of S-I, the 1997 flood crests would be lowered by 1.0 to 5.42 ft along the reach upstream of Pembina and by 0.85 ft at Emerson (Table 10). The crest at Wahpeton would be lowered by 5.42 ft and the crests at Fargo and Grand Forks would be reduced by 3.46 and 1.89 ft, respectively. Compared with that for S-I, the flood crests for S-II and S-III were predicted to be only 0.06 to 0.45 ft higher. This indicates that even 50% of the ultraconservative Waffle storage estimates would still have a measurable effect on reducing the flood crests along the Red River main stem. S-III would reduce the flood crests at Wahpeton, Fargo, and Grand Forks, North

Table 10. Predicted Reductions of the 1997 Flood Crests Along the Red River Main Stem

Station	Cross Section No.	Datum, ft	Maximum Water Surface Elevation, ft			
			Pre-Waffle	Scenario I (S-I)	Scenario II (S-II)	Scenario III (S-III)
Wahpeton (USGS 05051500)	XS 548.595	942.97	962.07	961.79	961.84	961.84
Hickson (USGS 05051522)	XS 485.041	877.06	914.70	909.28	909.44	909.58
Fargo (USGS 05054000)	XS 452.92	861.80	901.36	897.90	898.06	898.18
Halstad (USGS 05064500)	XS 375.247	826.65	867.31	865.93	866.00	866.05
Grand Forks (USGS 05082500)	XS 163	779.00	831.99	830.10	830.25	830.43
				[830.70]	[830.76]	[830.81]
				(831.51)	(831.54)	(831.67)
Oslo (USGS 05083500)	XS 107	772.65	810.95	809.92	810.45	810.53
				[810.25]	[810.65]	[810.67]
				(810.17)	(810.59)	(810.64)
Drayton (USGS 05092000)	XS 68	755.00	800.54	799.53	799.87	799.98
				[800.18]	[800.21]	[800.24]
				(800.10)	(800.15)	(800.21)
Pembina (USGS 05102490)	XS 16	739.45	794.39	793.29	793.35	793.44
				[793.97]	[793.99]	[794.01]
				(793.82)	(793.85)	(793.92)
Emerson (USGS 05102500)	XS 1	700.00	792.32	791.47	791.53	791.60
				[792.03]	[792.05]	[792.07]
				(791.91)	(791.94)	(791.99)

Note: The numbers in [ ] are for the combinations that the corresponding scenarios would be adopted for the watersheds upstream of Halstad but would not be adopted for the downstream watersheds. On the other hand, the numbers in ( ) are for the combinations that the corresponding scenarios would not be adopted for the watersheds upstream of Halstad but would be adopted for the downstream watersheds.

Dakota, by 5.12, 1.26, and 1.56 ft, respectively. At Emerson, the flood crest would be lowered by 0.72 ft. The predicted flow and water surface elevation hydrographs for the pre-Waffle condition, S-I, S-II, and S-III, at the nine locations are shown in Appendix C.

To further investigate potential Waffle storage effects, two additional storage combinations were formulated and analyzed for each of the three scenarios. Combination I assumes that Waffle storage would only be implemented in the watersheds upstream of Halstad and not downstream. In contrast, Combination II considers Waffle storage only in the watersheds downstream of Halstad. For example, the assumption for scenario S-I, Combination I is that the watersheds upstream of Halstad store 100% of the identified Waffle storage, whereas the watersheds downstream of Halstad contain zero Waffle storage.

In Table 10, the results for Combination I are presented in brackets and for Combination II in parentheses. Overall, the predicted flood crests for Combination I were higher than the corresponding values for Combination II, implying that Waffle storage in the watersheds downstream of Halstad would contribute to flood crest reductions along the reach from Halstad to Emerson. However, a close examination indicated that the contributions would only be as high as 0.15 ft for S-I and 0.09 ft for S-III. In contrast, the Waffle storage in the watersheds upstream of Halstad would be more important for reducing flood crests along the entire Red River main stem.

2.4.9 Evaluation of Moderate Waffle Storage Estimates

One of the key pieces of information needed by NDSU in conducting the economic analysis (Appendix H) was an evaluation of the Waffle effects for various-magnitude floods, both smaller and larger than 1997. Although the effects of the conservative storage estimates on the 1997 flood were explicitly modeled using SWAT and HEC–RAS, it was beyond the scope of the Waffle study to calibrate the models for a variety of hypothetical flood events. Thus the modeling results alone did not provide sufficient information to evaluate the economic feasibility of a wide range of Waffle storage scenarios for various-sized flood events. In addition, the EERC wanted to evaluate the moderate storage estimates described in Section 2.3 of this report for a variety of floods with flows larger than 1997.

In order to quickly evaluate a variety of different storage and flood magnitude scenarios, an algorithm was developed based on the relationship between storage volume and peak flow reductions observed through the SWAT modeling effort. This relationship for a given watershed (i.e., USGS 8-digit hydrologic cataloging unit) can be expressed by:

$$Y = 1.4638 + 4.6063 \cdot X + 2.8622 \cdot X^2 \qquad (R^2 = 0.84) \qquad [Eq. 6]$$

where Y is the peak reduction (%), and X is an independent variable.

Using $Q^{p}_{pre-waffle}$ and $Q^{p}_{post-waffle}$, in ft^3/sec, to signify the pre- and post-Waffle peaks, respectively, Y is computed as:

$$Y = \frac{Q^{p}_{pre-waffle} - Q^{p}_{post-waffle}}{Q^{p}_{pre-waffle}} \times 100\% \qquad \text{[Eq. 7]}$$

X is formulated as:

$$X = \ln(\frac{V_{waffle}}{Q^{p}_{pre-waffle}}) \qquad \text{[Eq. 8]}$$

Where V_{waffle} is the volume of Waffle storage in the watershed (acre-ft).

The 95% confidence interval for Equation 1 is determined as:

$$[-0.2659 + 2.1626 \cdot X + 2.0098 \cdot X^2, \qquad 3.1935 + 7.0500 \cdot X + 3.7146 \cdot X^2] \qquad \text{[Eq. 9]}$$

2.4.9.1 Prediction Accuracy

Equation 6 has a coefficient of determination (R^2) of 0.84, indicating a good prediction performance. Based on Figure 36, this equation can satisfactorily reflect the relationship between X and Y exhibited by the SWAT simulated data points (Figure 36). In addition, the good performance is verified by the fact that more than 62% of the data points fall in the 95% confidence interval computed using Equation 9 (Figure 37). Further, the prediction residuals from Equation 6 do not exhibit any clear pattern, i.e., the residuals do not have a consistent relationship with the SWAT simulated peak reductions (Figure 38). Therefore, Equation 6 may be a reliable model for use in estimating the peak reduction from a flood event with a peak discharge $Q^{p}_{pre-waffle}$ as a result of the Waffle storage volume V_{Waffle}.

2.4.9.2 Determination of Peak Reductions for Arbitrary Flood Events

Equation 6 was used to estimate the peak flow reduction for arbitrary flood events (e.g., flows twice as large as 1997), given various Waffle storage estimates for each watershed (moderate, conservative, etc.). For example, given that the 1997 peak discharge in the Rabbit River Watershed was 6185 ft^3/sec, to approximate the flow reduction for a flood event 200% larger than 1997 (double the flows) if 100% of conservative Waffle storage estimates (22,784 acre-ft) were used, the following calculation was conducted:

$$X = \ln(\frac{22{,}784}{2 \times 6185.00}) = 0.61078$$

$$Y = 1.4638 + 4.6063 \times 0.61078 + 2.8622 \times 0.61078^2 = 5.3\%$$

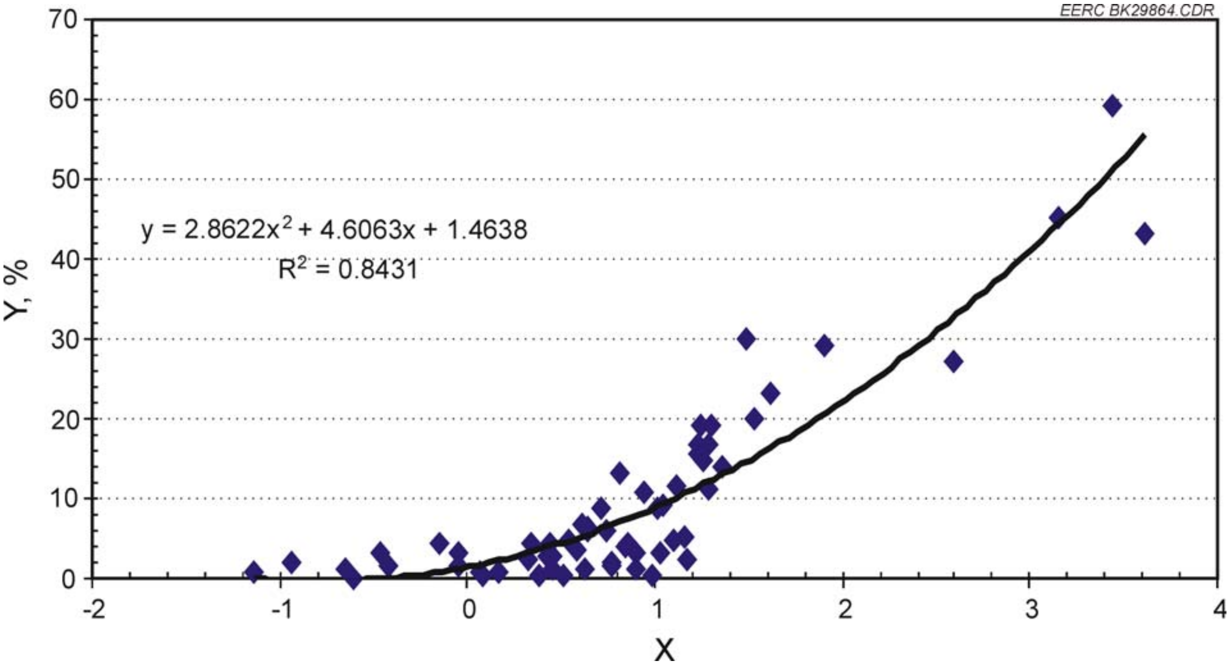


Figure 36. SWAT simulated data points and the curve represented by Equation 6.

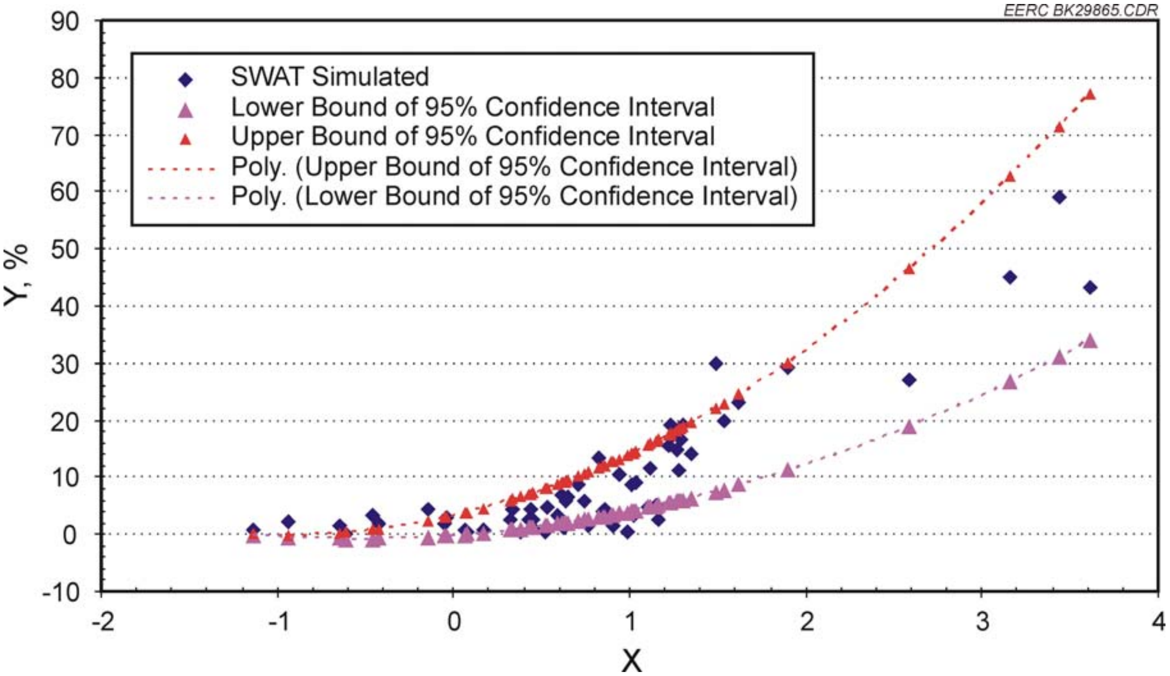


Figure 37. Distribution of SWAT simulated data points within the 95% confidence interval.

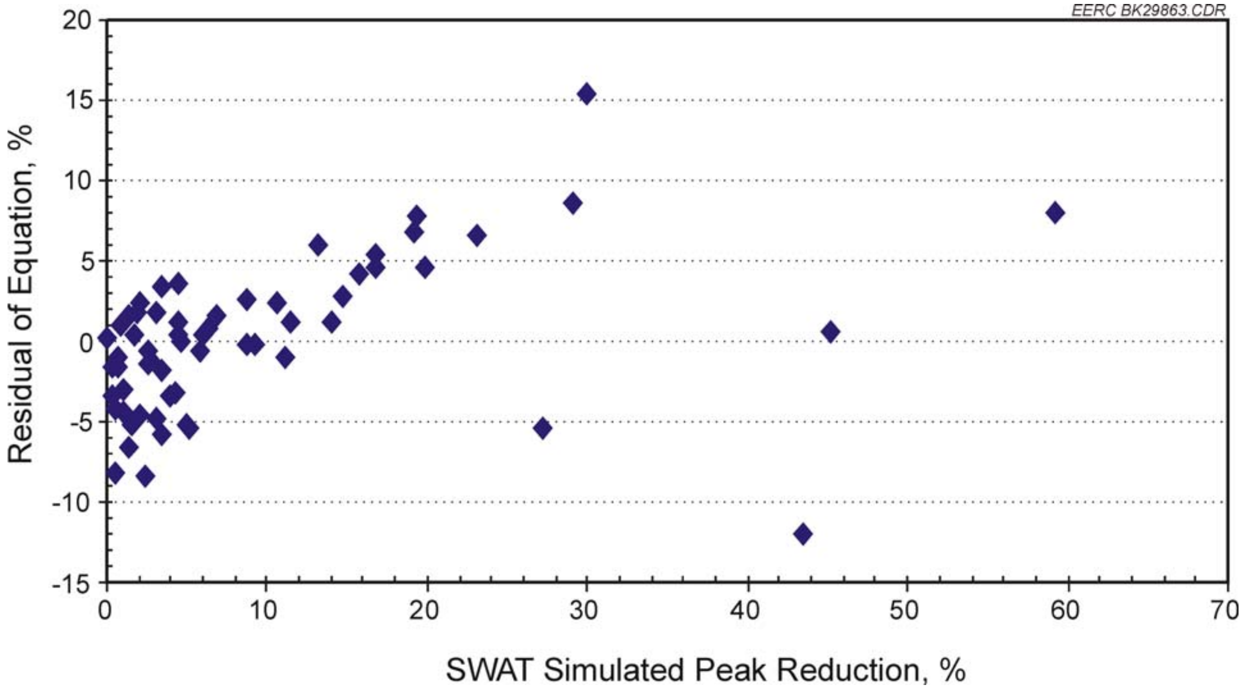


Figure 38. Comparison of residual points predicted from Equation 6 and SWAT simulated peak reduction.

Thus a 5.3% reduction in peak flows would be expected at the mouth of the Rabbit River by implementing 100% of the Waffle storage determined from conservative volume estimates.

The validity of this approach can be evaluated by comparing the predicted reduction in flows estimated by the above methodology to the flows predicted using the SWAT models (Table 11). Since only the conservative storage estimates were explicitly modeled using SWAT, the moderate storage estimates could not be used for comparison. The results compare well for most of the watersheds; however, in the comparison of revised flows for 100% of the conservative storage volume estimates, there are five watersheds with % errors larger than 15% (no errors were larger than 25%). These five watersheds include the Upper Red, Marsh, Grand Marais, Lower Red in Minnesota, and Lower Sheyenne in North Dakota. In the comparison of revised flows for 50% of the conservative storage estimates, two watersheds, the Grand Marais in Minnesota and the Bois de Sioux in North Dakota, have errors greater than 15%. Although these errors are larger than the preferred range of ±15%, the flow rates in the Upper Red and Grand Marais are so low after accounting for Waffle storage that they have little impact on the flows within the Red River. The remaining four watersheds with errors larger than ±15% for both storage scenarios have low to moderate flows and, therefore, slightly larger errors in these systems should not overly impact the relative storage reduction results.

To estimate the reduced peak flows at various locations along the main stem as a result of implementing Waffle storage, the adjusted flows from the tributaries upstream of various main

Table 11. Comparison of Flow Reductions Predicted Using the SWAT Models Versus the Empirical Equation Discussed Above

			Revised Flows: 100% of Conservative Storage Estimates			Revised Flows: 50% of Conservative Storage Estimates		
	Watershed Name	USGS HUC	Equation-Predicted Flows, cfs	SWAT-Predicted Flows, cfs	% Error	Equation-Predicted Flows, cfs	SWAT-Predicted Flows, cfs	% Error
MN Watersheds	Rabbit	9020101	5422	5000	−8.4	5854	5458	−7.3
	Mustinka	9020102	9915	9735	−1.8	9915	9830	−0.9
	Otter Tail	9020103	1556	1610	3.3	1615	1615	0.0
	Upper Red	9020104	611	510	−19.7	804	910	11.7
	Buffalo	9020106	8006	8575	6.6	8477	8640	1.9
	Marsh	9020107	6750	5540	−21.8	7361	7215	−2.0
	Wild Rice MN	9020108	10,139	10,095	−0.4	10,735	10,405	−3.2
	Sandhill	9020301	3970	4015	1.1	4282	4250	−0.7
	Red Lake	9020303	18,051	19,090	5.4	19,296	19,540	1.2
	Grand Marais	9020306	303	385	21.3	413	500	17.4
	Snake	9020309	14,480	13,835	−4.7	14,480	14,175	−2.2
	Lower Red	9020311	3890	3190	−21.9	3890	3480	−11.8
	Two Rivers	9020312	4158	4100	−1.4	4501	4445	−1.3
ND Watersheds	Bois de Sioux	9020101	2351	2080	−13.0	2428	2090	−16.2
	Wild Rice	9020105	7627	8084	5.6	8172	8296	1.5
	Elm	9020107	3880	3460	−12.2	4338	4120	−5.3
	Goose	9020109	6609	7430	11.1	7190	7554	4.8
	Lower Sheyenne	9020204	3907	4708	17.0	4324	4747	8.9
	Maple	9020205	6146	6488	5.3	6466	6537	1.1
	Wilson	9020301	5086	4780	−6.4	5471	5477	0.1
	Turtle	9020307	2095	2168	3.4	2213	2207	−0.3
	Forest	9020308	2790	2768	−0.8	2956	2906	−1.7
	Park	9020310	6498	6286	−3.4	7003	7335	4.5
	Lower Red	9020311	2928	2770	−5.7	3201	2999	−6.7

stem points were added together. Rating curves obtained from USGS and USACE were then used to estimate the corresponding stage at each main stem location. While this is not as accurate as using a hydraulic model like HEC–RAS to calculate the revised flows, it was sufficient for generating ballpark estimates. The effects of various Waffle storage estimates applied to floods smaller and larger than the 1997 flood (in terms of flows) were evaluated for Wahpeton–Breckenridge, Fargo–Moorhead, Grand Forks–East Grand Forks, and Drayton. The results for each location are shown in Tables 12–15.

Table 12. Estimated Red River Flow and Stage Reductions at Wahpeton as a Result of Various Waffle Storage Estimates

	50% of 1997 Flows, cfs		1997 Flows, cfs		125% of 1997 Flows, cfs		150% of 1997 Flows, cfs		200% of 1997 Flows, cfs	
	Flow w/out storage: 10,072 cfs; Stage = 17.54 feet		Flow w/out Storage: 20,143 cfs; Stage = 23.43 feet		Flow w/out Storage: 25,179 cfs; Stage = 25.80 feet		Flow w/out Storage: 30,215 cfs; Stage = 27.89 feet		Flow w/out Storage: 40,286 cfs; Stage = 31.56 feet	
	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction
Moderate Storage Estimates	7097	2.34	16,430	1.92	21,290	1.82	26,222	1.66	36,225	1.41
50% of Moderate Storage Estimate	8215	1.40	18,113	1.02	23,170	0.94	28,394	0.75	38,488	0.63
Conservative Storage Estimate	9056	0.73	19,241	0.43	24,319	0.40	29,409	0.33	39,625	0.23
50% of Conservative Storage Estimate	9622	0.31	19,812	0.16	24,894	0.12	29,980	0.09	40,286	0.0

Table 13. Estimated Red River Flow and Stage Reductions at Fargo as a Result of Various Waffle Storage Estimates

	50% of 1997 Flows, cfs		1997 Flows, cfs		125% of 1997 Flows, cfs		150% of 1997 Flows, cfs		200% of 1997 Flows, cfs	
	Flow w/out Storage: 14,961 cfs; Stage = 33.01 feet		Flow w/out Storage: 29,922 cfs; Stage = 39.94 feet		Flow w/out Storage: 37,402 cfs; Stage = 41.87 feet		Flow w/out Storage: 44,882 cfs; Stage = 43.25 feet		Flow w/out Storage: 59,843 cfs; Stage = 45.35 feet	
	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction
Moderate Storage Estimates	6760	7.7	16,117	6.2	21,084	5.7	26,153	4.8	36,495	3.7
50% of Moderate Storage Estimate	8059	5.8	18,247	5.1	23,509	4.5	28,924	3.7	39,574	3.0
Conservative Storage Estimate	9124	4.5	19,785	4.4	25,164	3.8	30,573	3.1	41,455	2.6
50% of Conservative Storage Estimate	9894	3.8	20,728	3.9	26,165	3.4	31,611	2.7	42,673	2.4

Table 14. Estimated Red River Flow and Stage Reductions at Grand Forks as a Result of Various Waffle Storage Estimates

	50% of 1997 Flows, cfs		1997 Flows, cfs		125% of 1997 Flows, cfs		150% of 1997 Flows, cfs		200% of 1997 Flows, cfs	
	Flow w/out Storage: 55,769 cfs; Stage = 45.22 feet		Flow w/out Storage: 111,537 cfs; Stage = 54.20 feet		Flow w/out Storage: 139,421 cfs; Stage = 57.61 feet		Flow w/out Storage: 167,306 cfs; Stage = 59.77 feet		Flow w/out Storage: 223,074 cfs; Stage = 62.55 feet	
	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction
Moderate Storage Estimates	31,030	9.2	77,665	5.0	102,616	4.6	128,211	3.4	180,757	2.1
50% of Moderate Storage Estimate	38,833	4.9	90,378	3.0	117,273	2.6	144,723	1.6	200,054	1.2
Conservative Storage Estimate	45,189	2.5	100,024	1.5	128,057	1.3	156,309	0.6	213,457	0.5
50% of Conservative Storage Estimate	50,014	1.2	106,729	0.7	135,400	0.5	163,784	0.2	221,140	0.1

Table 15. Estimated Red River Flow and Stage Reductions at Drayton as a Result of Various Waffle Storage Estimates.*

	50% of 1997 Flows, cfs		1997 Flows, cfs		125% of 1997 Flows, cfs		150% of 1997 Flows, cfs	
	Flow w/out Storage: 69,646 cfs; Stage = 42.63 feet		Flow w/out Storage: 139,292 cfs; Stage = 47.31 feet		Flow w/out Storage: 174,115 cfs; Stage = 48.96 feet		Flow w/out Storage: 208,938 cfs; Stage = 50.37 feet	
	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction
Moderate Storage Estimates	40,269	3.7	99,336	2.4	130,842	2.1	163,110	1.9
50% of Moderate Storage Estimate	49,668	2.1	114,617	1.4	148,401	1.2	182,803	1.1
Conservative Storage Estimate	57,309	1.2	126,067	0.7	161,161	0.6	196,425	0.5
50% of Conservative Storage Estimate	63,097	0.6	133,794	0.3	169,484	0.2	204,843	0.2

* The estimates for 200% of 1997 flows were not determined for this location because the flows far exceeded those on the USGS rating curve and, therefore, accurate stage reductions could not be determined.

For comparison, the 1997 flood crest reductions that were modeled using SWAT and HEC–RAS for 100% and 50% of conservative estimates are listed in Table 16 along with the equation-predicted results. The two different techniques predicted similar results for Wahpeton; however, the equation-predicted stage reductions were slightly higher for Fargo and slightly lower for Grand Forks and Drayton. For consistency among all evaluation scenarios, the economic evaluation used the equation-derived numbers for the 1997 flood and not those explicitly modeled. This may lead to a slightly higher estimate of damage mitigated in Fargo and a slightly lower prediction of damage mitigated in Grand Forks and Drayton.

2.4.9.3 Limitations and Empirical Adjustments

In the event that the above equations are used in the future, it is worth mentioning some of the limitations of the method discussed above and a correction factor that was applied to account for attenuation of flows along the main stem. For a location of interest along the main stem, this procedure does not consider timing of the peaks from the corresponding contributing watersheds. In addition, between two adjacent locations (e.g., from Fargo to Halstad), the procedure assumes no attenuation of the peaks. These assumptions could result in either the overestimation or underprediction of the peak at the location of interest. To address this issue, the HEC–RAS model was used to evaluate the attenuation effects along the main stem. The evaluation indicates that for the existing or pre-Waffle conditions, the attenuation effects are negligible for the 1997 flood. That is, the attenuation coefficients are close to a factor of one. For post-Waffle conditions, the attenuation effects for most reaches of the main stem (i.e., from Fargo to Halstad, Halstad to Grand Forks, Grand Forks to Drayton, and Drayton to Emerson) were small; however, this was not the case with the reach between Wahpeton and Fargo–Moorhead. The attenuation coefficient for the reach from Wahpeton to Fargo–Moorhead was determined to be approximately 0.72 after implementation of 100% of conservative storage estimates, whereas the coefficients for the other reaches were determined to be greater than 0.95. These attenuation effects are affected by altered timing of flows, friction along the river banks, and the width of the inundated floodplain. Therefore, it is recommended that the computed peaks at Fargo–Moorhead using the aforementioned procedure be multiplied by a coefficient of 0.72. This coefficient is reflected in the Fargo numbers listed in Table 13. Because attenuation effects along the other reaches were within a 5% margin of error, an attenuation coefficient was not applied to the other main stem reaches.

Table 16. 1997 Flood Crest Reductions Modeled Using SWAT and HEC–RAS for the 100% and 50% Conservative Estimates

	100% Storage: Conservative Estimates		50% Storage: Conservative Estimates	
Location	Modeling-Predicted Stage Reduction, ft	Equation-Predicted Stage Reduction, ft	Modeling-Predicted Stage Reduction, ft	Equation-Predicted Stage Reduction, ft
Wahpeton	0.3	0.4	0.3	0.2
Fargo–Moorhead	3.6	4.4	3.3	3.9
Grand Forks	2.0	1.5	1.6	0.7
Drayton	1.0	0.7	0.8	0.3

The procedure described above was designed to predict overall trends and relative changes between existing and post-Waffle conditions. It was used mainly to extrapolate the results for the 1997 flood to larger floods and to evaluate various Waffle storage volumes to provide a range of Waffle effects for use in the economic analysis. For these purposes, the procedure is sufficiently accurate. However, to more accurately predict "true" peak discharges along the main stem, a hydraulic model such as HEC–RAS should be used.

2.4.10 Modeling Conclusions and Recommendations

This study evaluated the effects of the Waffle on flood reduction in the RRB using coupled SWAT and HEC–RAS hydrodynamic models. The SWAT models were set up for 31 modeling domains, of which 17 are located in Minnesota and the other 14 in North Dakota. A modeling domain was defined in terms of USGS 8-digit HUCs; however, watersheds that spanned both states were redelineated into two components – one for the North Dakota side of the RRB and one for the Minnesota side of the watershed. The available data on observed daily stream flows for the 1997 flood were used to calibrate the SWAT models. When the data were unavailable, the models were verified based on scientific judgment and/or peak discharge values obtained from various sources (e.g., consulting companies). In addition, the Minnesota SWAT models and one North Dakota model were validated using other historical floods that occurred in 1979, 1978, 1975, 1969, and 1966. Statistical parameters used to determine the calibration and/or validation results indicated that the SWAT models are accurate enough for evaluating the effects of the Waffle. Further, both ACE-M, the HEC–RAS model for the main stem reach from White Rock Dam to Halstad, and EERC-M, the HEC–RAS model for the reach from Halstad to Emerson, were calibrated in accordance with the 1997 flood.

The most conservative Waffle storage estimates were used as input into the SWAT models for evaluation of peak flow reductions. The SWAT model results showed that conservative Waffle storage volumes would reduce peak flows along the tributaries from less than 1% to as high as 59.2%. The reduction effects are a function of the ratio of Waffle storage volumes to watershed area, the spatial distribution of the Waffle storage locations, the shape of the watershed, and the characteristics of individual floods (i.e., magnitude and hydrograph shape).

Results of the HEC–RAS modeling indicate that the conservative Waffle storage volumes would lower the 1997 flood crests by 1.0 to 5.42 ft along the Red River upstream of Pembina and by 0.85 ft at Emerson. The Waffle would have a more pronounced effect on reducing main stem flood crests from just downstream of Grand Forks to Halstad and from approximately 18 mi downstream of Fargo to about 5 mi upstream of the Richland County Road 28 near Abercrombie. In addition, Waffle storage in the watersheds upstream of Halstad would be more important for reducing the flood crests along the entire main stem than that in the downstream watersheds.

To provide additional estimates of the Waffle effects for various storage estimates and for hypothetical flood events smaller and larger than 1997, an equation was developed based on the SWAT modeling results. The equation relates the volume of Waffle storage to predicted reduction in peak flows at the mouth of each RRB tributary. To equate the peak flow reductions within each of the tributaries to flow reductions along the Red River, the upstream flows contributing to key points along the Red River were added together. The flows from the

Wahpeton to Fargo reach of the Red River were further adjusted to account for attenuation, based on the attenuation of flows observed using the HEC–RAS model. Attenuation in the other reaches of the Red River was negligible and, therefore, not taken into account. Using this method, several Waffle storage volumes were evaluated, including 100% and 50% of moderate estimates and 100% and 50% of conservative estimates. In addition to the 1997 flood, several hypothetical flood events with flows smaller or larger than 1997 were evaluated, including 50%, 125%, 150%, and 200% of 1997 flows. Estimated stage reductions ranged from 0 to 2.43 feet at Wahpeton; 2.4 to 7.7 at Fargo; 0.1 to 9.2 at Grand Forks; and 0.2 to 3.7 at Drayton.

To further enhance these research results and the models developed through this study, we recommend the following:

- The North Dakota SWAT models should be validated using other historical flood events.
- The HEC–RAS models should be validated using other historical flood events.
- An interface should be developed to automate the data transfer from the SWAT models to the HEC–RAS models.
- Additional Waffle storage scenarios and various flood magnitudes should be analyzed to identify a set of optimal or cost-effective options to achieve the highest stage reductions with the least amount of Waffle storage.
- The models should be expanded and enhanced for other studies, such as evaluation of water supplies during drought conditions and watershed-based water quality assessments.

2.5 Waffle Field Trials

2.5.1 Introduction and Objectives

The Waffle field trials were conducted to demonstrate the Waffle flood mitigation concept and to evaluate the potential impacts of short-term water storage on the landscape. A key goal of the field trials was to quantify the effects of Waffle storage on flows in waterways immediately adjacent to the trial sites and to understand the potential effects of the water storage on the physical and chemical characteristics of land with varying uses and soil types.

The Waffle field trials were conducted over a period of 3 years from the spring of 2004 to the spring of 2006. The initial field trial, conducted on a parcel of agricultural land in Minnesota, allowed testing of the instrumentation and methods to be utilized in the subsequent field trials. The second-year field trials were conducted on four parcels of land in both Minnesota and North Dakota and assessed a variety of parameters including potential flow reductions, soil chemistry, water quality, soil moisture, soil temperature, crop yields, and impacts to road stability. The final field trial was conducted on a parcel of land in Minnesota strictly for the purposes of evaluating road stability and flow reductions.

2.5.2 Methodology

2.5.2.1 Site Selection

Three sites in Minnesota and one site in North Dakota were utilized for the field trial demonstrations. Figure 39 illustrates the site locations with respect to the RRB. Each site was chosen based on availability (i.e., landowner willingness to participate) and desirable characteristics such as location within the basin, soil type, and land use/land cover. Site characteristics are listed in Table 17.

2.5.2.2 Site Descriptions

Shelly Site: The Shelly site, located approximately 5 miles southeast of the city of Shelly, Minnesota, is an agriculture-dominated parcel of land with approximately 150 acre-ft of water storage capacity. The site is a full square mile of land (640 acres) bounded by county and township roads on all four sides. A plan view of the site is illustrated in Figure 40. The land slopes approximately 6 feet from the eastern most edge of the section to the western edge, and drainage from the site occurs through culverts located in both the northwest and southwest corners of the section. The water flows from the site into two adjacent, west-flowing judicial ditches on the north and south sides of the section that eventually empty into the Marsh River which, in turn, drains to the Red River. The parcel is characterized by clay and clayey-loam soils, and the dominant crop types during the trial years were corn and sunflowers. Storage occurred in the eastern portion of the section and covered an area of approximately 80 acres with varying water depths. This site was chosen for the opportunity to evaluate the effects of water storage on agricultural land. Figure 41 shows the culvert standpipe and water storage during the spring 2004 demonstration.

Agassiz Wildlife Refuge Site: This trial site is situated on a 320-acre parcel of land located approximately 10 miles northeast of the city of Holt, near the Agassiz Wildlife Refuge in

Table 17. Physical Characteristics of Each Water Storage Site

Site	Land Use	Crop Types	Soil Type	Estimated Flooded Area, acres	Estimated Water-Holding Capacity, acre-ft
Gilby	Conservation Reserve Program (CRP)	–	Clay to clay–loam	150	200
Shelly	Agriculture	Corn, Sunflowers	Clay–loam	80	150
Lake Bronson	CRP	–	Fine-, medium-grained sand	65	145
Agassiz Refuge	CRP	–	Sandy, clay–loam	60	150

Figure 39. Location of Waffle field trial sites.

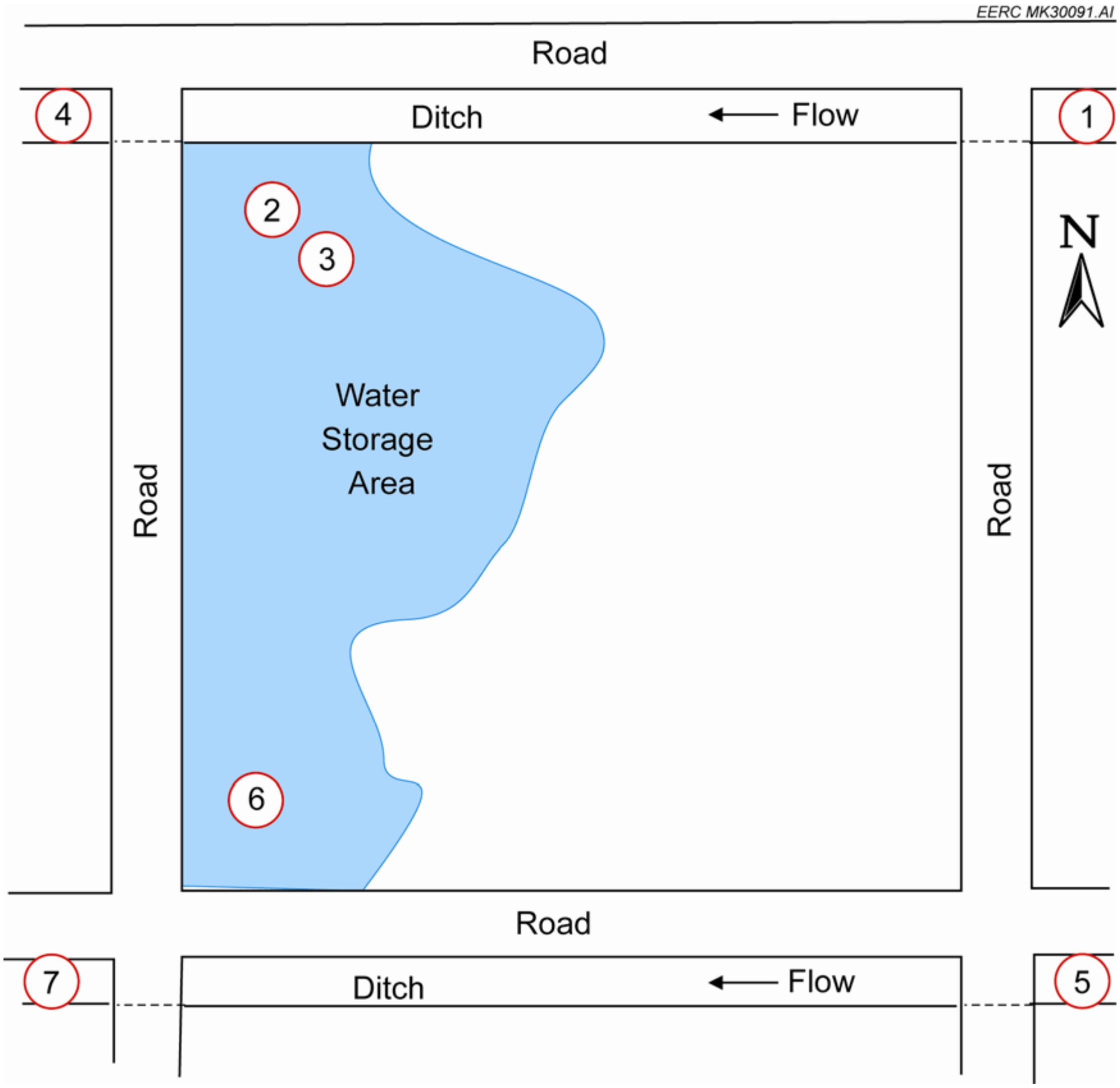


Figure 40. A plan view of the Shelly field trial site. The numbers correspond to water sample locations.

EERC MK26338.CDR

Figure 41. Shelly field trial site at full storage (spring 2005).

north central Minnesota approximately 60 miles east of the Red River. A plan view of the site is illustrated in Figure 42. The land was enrolled in CRP at the time of the demonstration and was contained within a ring dike levee next to a judicial ditch that drains from a large retention pond associated with the refuge system. Runoff from the parcel is discharged to the adjacent judicial ditch through four small (24-inch) culverts. The ditch ultimately drains into the Red Lake River. The soil on the parcel is predominantly a sandy clay–loam with an underlying thick layer of peat material. This site was chosen based on its distance from the Red River, which helps reduce flows far upgradient in the basin and its unique dike containment that made it ideal for water retention. This site had a potential capacity of over 500 acre-ft of water storage; however, because it is isolated from the drainage system, it can only store the equivalent volume of precipitation that falls directly on the land, which is approximately 150 acre-ft during years with average precipitation. Figure 43 shows one of the four Agassiz site culverts at maximum water storage.

Lake Bronson Site: This site is located approximately 2 miles south of the city of Lake Bronson, Minnesota, and it is also enrolled in CRP. The parcel is a 640-acre section of land that is bounded by paved county roads on the west and north sides and by gravel county and township roads to the east and south, respectively. A plan view of the site is illustrated in Figure 44. A small coulee runs through the section from east to west and flows under the county highway through a 52-inch concrete culvert. The coulee is a natural drainage outlet for approximately 6 square miles of land to the east known as the Halma Swamp. The precipitation

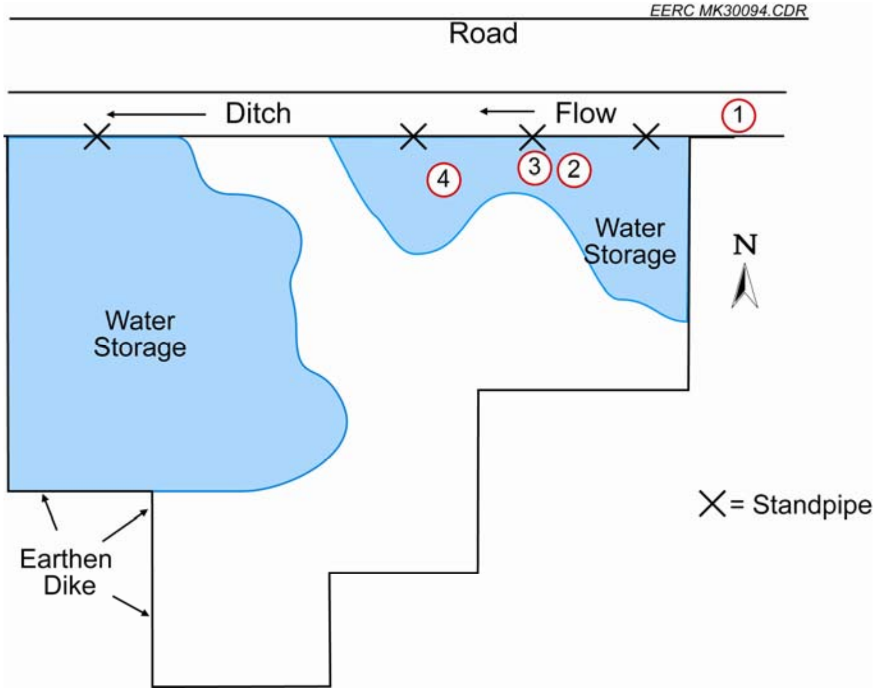


Figure 42. A plan view of the Agassiz field trial site. The numbers correspond to water sample locations.

Figure 43. Agassiz Wildlife Refuge field trial site at full storage (spring 2005).

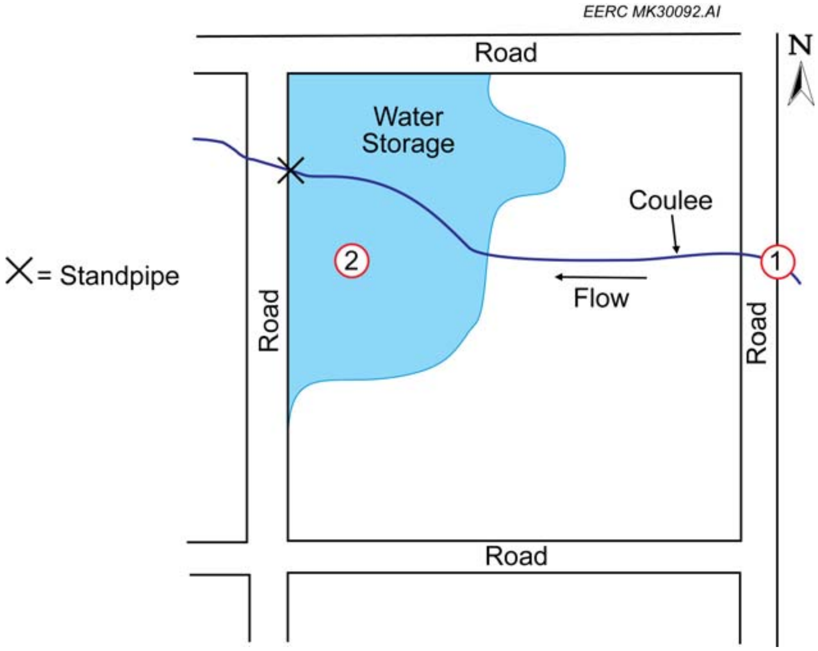


Figure 44. Plan view of the Lake Bronson field trial site. The numbers correspond to water sample locations.

that falls on the field trial section is drained by the coulee. The relief of the parcel is approximately 5 feet, sloping from the east to the west side. The majority of water storage during the trials was located on approximately 65 acres in the northwestern corner of the parcel and was equivalent to a predicted capacity of 145 acre-ft. The soil type on the parcel is predominantly fine- to medium-grained sand with sporadically located cobbles. This site was chosen because the upstream runoff could be captured via the coulee, ensuring adequate amounts of storage even in a low-precipitation winter. Another desirable characteristic of the site was the newly paved road bordering the section to the west that could be instrumented to assess road stability. Figure 45 illustrates the water storage as it occurred during the spring 2005 melt.

Gilby Site: This site, located approximately 2 miles east of the city of Gilby, North Dakota, is also enrolled in CRP and is dominated by cattails and other wetland vegetation. This parcel of land is also a 640-acre square-mile section with a dike system bounding the south, east, and north sides. A plan view of the site is illustrated in Figure 46. Two 30-inch culverts drain the excess water into adjacent judicial ditches; however, the culvert placement was designed to maintain a shallow (1–2 feet) water level throughout the year to create a wetland environment. A total predicted storage capacity of 200 acre-ft, in addition to the normal wetland level, was estimated at this site. The soil on this site is clay to clayey loam. The soil chemistry at the site was representative of that found in areas characterized by saline groundwater discharge from the Dakota Aquifer system. These areas tend to occur in a north–south-trending zone approximately 10 to 30 miles west of the Red River (Gerla, 1992). The groundwater discharge from the Dakota Aquifer system is relatively high in dissolved minerals and salts, and these soluble constituents become concentrated in the soils through evaporation (Gerla, 1992).

Figure 45. Lake Bronson field trial site at full storage (spring 2006).

The soil chemistry made this location a desirable site to evaluate the potential dissolution of salts from the soils into the water stored at the site. Figure 47 is an aerial photograph of the Gilby site during the spring 2005 demonstration.

2.5.2.3 Surveying

Prior to equipment installation or culvert modifications, a detailed elevation survey was conducted at each site to determine potential storage volumes and to ensure that the drainage of neighboring sections would not be altered. The surveying was conducted using a survey-grade global-positioning system (GPS). Several thousand data points were collected across each site to develop an accurate representation of the land surface, to determine where water would accumulate, and to evaluate the drainage system response to temporary water storage (i.e., as a result of culvert modifications). The data points were collected either using a surveying receiver mounted on an all-terrain vehicle (ATV), or a handheld staff, and traversing the entire site and adjacent roads. The data points were utilized to construct a detailed topographic map of the sites to predict where the water would accumulate and at what depth. A topographic map showing

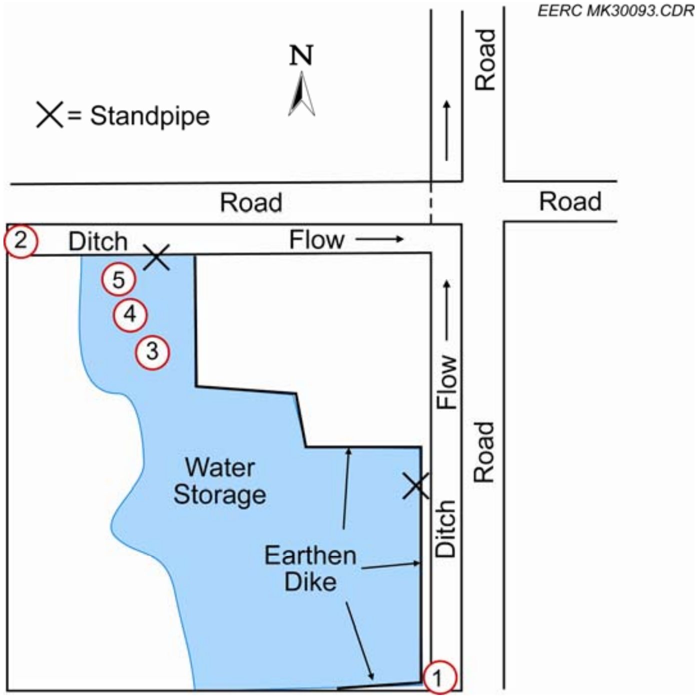


Figure 46. Plan view of the Gilby field trial site. The numbers correspond to water sample locations.

the areas where water would be stored and the approximate water depths at the trial site located near the Agassiz Wildlife Refuge is shown in Figure 48. The elevations of the existing culverts were also measured and used in the culvert modification design process.

2.5.2.4 Culvert Designs and Modifications

After a review of the elevation data collected at each trial site, the existing culverts were modified with canal gates and overflow standpipe devices, shown in Figure 49, to allow for water retention on the site up to a specified elevation. The selected elevation was designed to maximize storage and ensure that sufficient freeboard existed to protect adjacent roads against potential wave erosion resulting from high winds or overtopping in the event of heavy rains. Several different culvert modification approaches were contemplated prior to selecting the design that was implemented. The culvert design selection took into account many factors such as functionality, safety, and the temporary nature of the demonstration. These culvert designs were then submitted to county engineers for their comment and approval. In the case of future implementation of the Waffle concept, culvert designs may be modified to accommodate more permanent site placement.

Figure 47. Aerial photo of Gilby field trial site at full storage.

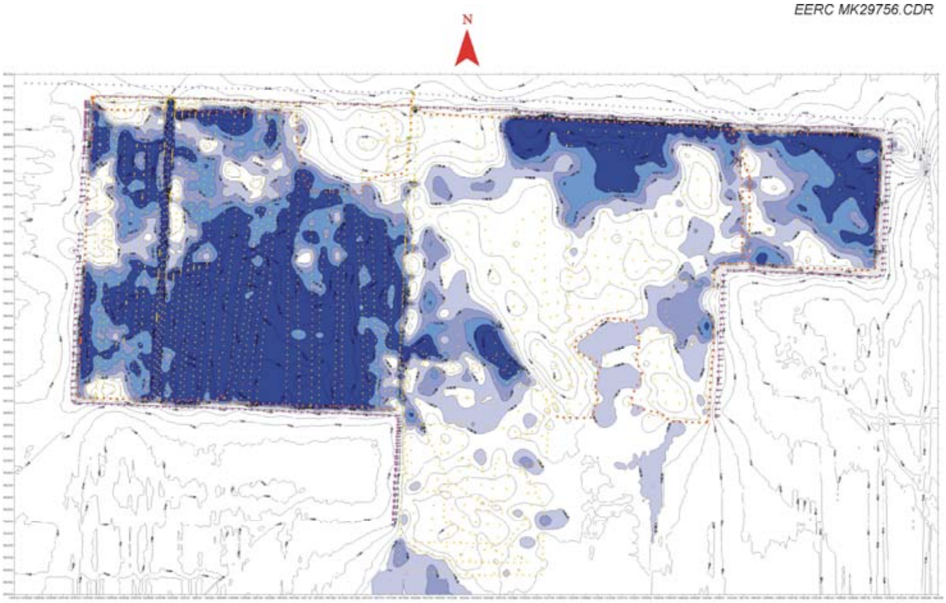


Figure 48. Topographic map of the Agassiz Refuge field trial site showing predicted water storage areas.

EERC MK29755.CDR

Figure 49. Culvert modification devices (standpipe and canal gate).

Because the gated culvert standpipes become buoyant when the gated culverts are closed and water levels rise, a set of cable anchors were used to hold the entire culvert assembly in place. Depending on the size of the culvert–standpipe assembly and its associated buoyancy potential, steel cable anchors of various size were driven into the ground and fastened to each culvert.

Trash racks were also added to the standpipes to keep large debris from passing into the culvert and obstructing flow. The design for these trash racks was modified from a design used by the Minnesota Department of Transportation (MNDOT) and NRCS. An example of these trash racks can be seen in Figures 41–43.

2.5.2.5 Permit Requirements

In order to modify existing culverts and store water on the selected demonstration sites, a variety of approvals and permits were required. The required approvals and permits identified through this project included the following:

- Landowner agreements
- County or state engineer permits
- Watershed district permits (Minnesota)
- Water board permits (North Dakota)
- Ditch authority approval
- County and state Farm Service Agency (FSA) contract approval (if on CRP acreage)

The first step in the process was to obtain permission from all landowners within the selected field trial location. Contracts between the EERC and each landowner were executed to grant the EERC permission to temporarily retain spring runoff and allow access to the land to install instrumentation for monitoring purposes. Once landowner permission was obtained, several other state and local entities were contacted to obtain the required permits for manipulating the existing culverts and drainage patterns.

In order to modify the existing culverts with canal gates and standpipes for water retention, a permit was required by the county or state engineer (depending on whether it was a county- or state-owned culvert) and also by the Watershed District (if the site was in Minnesota) or the Water Resource Board (if the site was in North Dakota). To obtain the county or state engineer permit, an application that included a detailed description of the culvert modifications was required, which had to meet all road right-of-way safety standards. For example, standpipes were required to be located at a designated distance from the shoulder of the road and had to be equipped with safety reflectors. The Watershed District and Water Resource Board applications also required a detailed description of the proposed culvert modifications, the potential drainage system impacts, and the elevation of the water surface at maximum storage capacity. A topographic map, created using GPS data collected at each site, was also included with each application to illustrate the expected location of water storage.

In Minnesota, the County Ditch Authority (CDA) required board approval be obtained for any project that would affect the drainage of, or into, any legal ditch within each county. The approval process was initiated by submitting a letter that described the project and the anticipated length of implementation. The main concern of the CDA is flow capacity of the waterway and potential erosion problems around culverts. These concerns were addressed in the application letter.

The final approval obtained for the field trial demonstrations was from the Minnesota FSA at both the county and state levels. This approval was needed to conduct research on land enrolled in CRP. The approval process required the submittal of a letter describing the project and a listing of the CRP contracts that would be affected. At the time of this project, FSA was in the process of establishing temporary water storage as a legal activity on CRP-enrolled land without affecting landowner contracts. Therefore, the future approval requirements may be different if water storage is added to the list of acceptable activities on CRP land.

2.5.2.6 Site Instrumentation

A series of instruments were installed at each site to evaluate the physical characteristics of the trial locations. Meteorological stations, as shown in Figure 50, were set up at all four sites to obtain data on variables such as wind speed, wind direction, temperature, humidity, precipitation, and solar radiation. These data were used to derive information about potential evaporation losses, temperature fluctuations, and the amount of moisture added through rain and snow. The data were stored and periodically downloaded from a solar-powered data logger attached to each station. These stations were installed in late October and were removed in late June of each season.

EERC MK29757.CDR

Figure 50. Photograph of meteorological station being installed.

Soil moisture and temperature data were collected at three of the demonstration sites to provide information on frost thaw rates and soil moisture levels at varying depth during and after water storage. The temperature and moisture data were measured in both the flooded and nonflooded areas of each demonstration site. The temperature data were collected using individual temperature dataloggers that were buried in the soil at 4-inch intervals to a maximum depth of 24 inches below the surface. Each datalogger was programmed to record a temperature reading every 6 hours for approximately 6 months. At the completion of the demonstration, all sensors and dataloggers were removed from the sites.

Soil moisture data were collected with soil moisture sensors installed every 4 inches to a depth of 32 inches below the surface. Each sensor was connected to a micrologger that recorded moisture content every 6 hours for the same 6-month period. All data from the dataloggers were downloaded to a laptop computer on a monthly basis to ensure that any data loss would be minimized in the event of battery failure. At the end of the demonstration, all data files were merged for analysis with the associated sensor software.

A key component of the field trial demonstration was to document the reduction in flows resulting from the temporary storage of water. To achieve this objective, the culverts that drained the storage site were instrumented with flow-measuring devices containing built-in dataloggers. The flows in adjacent ditches or waterways were also measured before, during, and after the water storage period to evaluate the impact on flows in adjacent ditches and waterways. The flow was monitored by placing a pressure transducer into a polyvinyl chloride (PVC) stilling well to record water depths over time, and water flow velocities were periodically monitored using a handheld stream flow gauge. A photograph of a stilling well is shown in Figure 51. Channel cross sections, water depths, and flow velocity were used to determine flow and develop hydrographs for individual sites. The flow data were also used for comparison to nearby river stages and to Red River stages to evaluate the timing of water release with respect to peak flows and associated river levels.

To understand the impacts of storing water against roadbeds, a series of temperature and moisture sensors were installed in two locations across a road adjacent to the Lake Bronson trial site. The first sensor array was instrumented in a section of the road that was adjacent to the water storage location at the trial site. The second sensor array was located in a road section south of the trial site that was adjacent to an area that remained dry during the entire spring melt. A diagram of the sensor placement is shown in Figure 52. The sensors were placed in an acrylic rod and installed in a borehole placed at 6-ft intervals extending across the entire roadbed and out to the bottom of the ditch. The individual sensors were spaced every 6 inches from the surface to a total depth of 6 ft. A total of eight boreholes were instrumented. Figure 53 illustrates one of the boreholes instrumented with a sensor array. Sensors in each borehole were connected to a datalogger on the side of the road. Figure 54 shows the pavement being removed to accommodate sensor placement and datalogger connections.

EERC MK29758.CDR

Figure 51. Photograph of stilling well used to monitor culvert water levels.

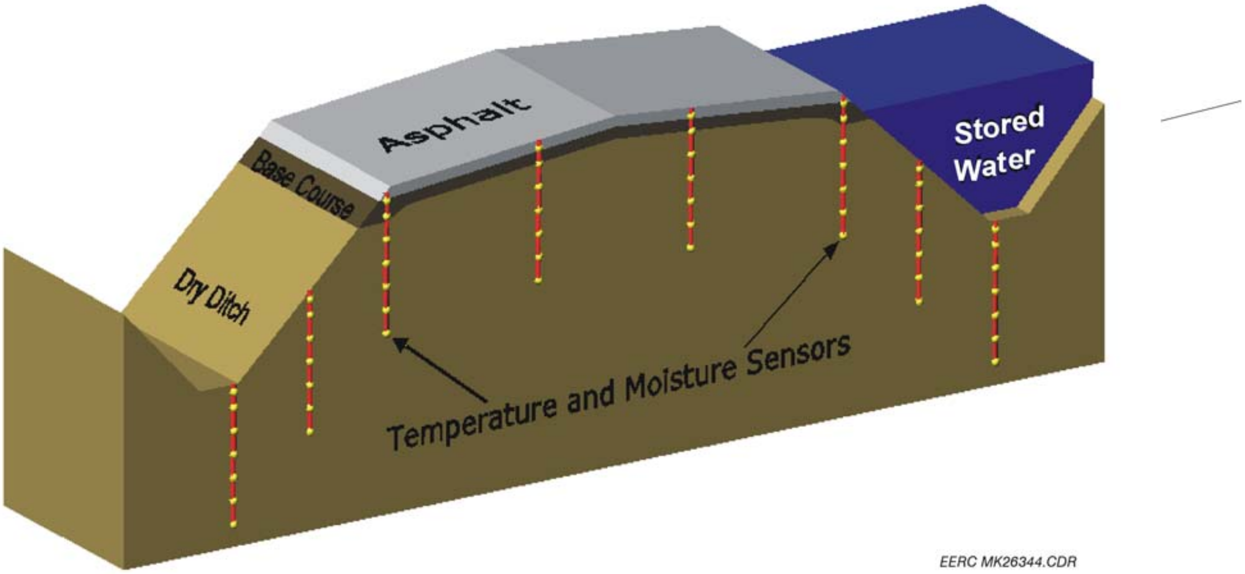


Figure 52. Cross section of road illustrating sensor placement.

Figure 53. Acrylic rod containing sensors in a borehole within the road.

Figure 54. Installation of sensors in cross section of road.

2.5.2.7. Soil Sampling and Analysis

To evaluate the potential impacts of water storage on soil chemistry, soil samples were collected from flooded and nonflooded areas of the Shelly and Gilby trial sites and analyzed for 15 different parameters. Soil samples were collected at depths to 42 inches using a ¾-inch-diameter, direct-push soil probe. The core samples were sectioned according to depths representing zones from 0 to 6 inches, 6 to 24 inches, and 24 to 42 inches. Approximately 20 core sample segments were composited, homogenized, and submitted to Energy Laboratories, Inc., for analyses. Because of the heterogeneous nature of soils, several samples from each depth were analyzed to allow for the determination of an average concentration. The results were used to calculate an average value and standard deviation for each analyte at both locations. The soils were analyzed for nitrates, phosphorus, sodium, organic matter, soluble salts, etc. The soils at both sites were collected and analyzed prior to water storage in the fall and again in the spring after the water had been stored and the soils dried. The Shelly site demonstration was conducted in two consecutive years, and soil samples were collected and analyzed each year. The Gilby site soils were only analyzed during the spring 2005 demonstration.

2.5.2.8 Water Sampling and Analysis

A water quality evaluation was conducted on all four field trial demonstration sites. The collection and analysis of water samples at varying locations within the storage area and the adjacent drainage systems were conducted to determine whether chemical constituents or residues within the site soils would dissolve into the stored water, especially considering that the soils would be in contact with the water longer than previously experienced prior to Waffle storage. Given this objective, water samples were collected at varying time intervals at each site during water storage and in the adjacent drainage systems after water was released from the site. The adjacent drainage systems (i.e., ditches or coulees) were sampled both upgradient and downgradient of the stored water to determine water quality changes resulting from the extended storage of water on the site and ultimate release into the waterway. The water samples were shipped to an analytical laboratory for analysis of more than 50 standard parameters, such as conductivity, pH, turbidity, nitrates, various metals, pesticides, and herbicides. Replicate and duplicate samples were also submitted for quality control purposes. Also, duplicates of various samples were submitted to a second laboratory for additional quality control purposes.

2.5.3 Results

2.5.3.1 Flow Reduction Evaluation

To determine the downstream flood reduction potential of the Waffle field trial sections, water levels and associated flows were measured in culverts draining the site and in adjacent ditches and/or waterways. Initially, all sites were instrumented with flow-monitoring equipment; however, vandalism and large ice flows damaged some equipment and limited useful measurements to two of the sites. The flows were monitored at the Shelly site in 2004 and the Lake Bronson site in 2005 and 2006.

For comparison with measured flow data, the predicted flows for each site without Waffle storage were determined using the Storm Water Management Model (SWMM). The measured flows with Waffle storage versus the modeled flows without storage are shown for each site in Figures 55–57.

In 2004, the water at the Shelly site was held back from the adjacent drainage ditch for 14 days. The initial reduction in peak flows in the ditch was approximately 10%–15%. However, between March 30 and March 31, the ditch flow began to decrease as an ice jam in the ditch 1 mile downstream of the site impeded the drainage. On approximately April 1, this ice jam melted and broke loose and the flows in the ditch increased dramatically, as can be seen in Figure 55. The flows with and without Waffle storage are then almost identical until April 8 because the field trial section was at full storage and the ditch was conveying extremely high flow resulting from the ice jam breakup. On April 9 the water was released from the field trial section, resulting in an increase in flow, which can be seen in the flow hydrograph. This increased flow is much lower than the previous peak flows observed during the height of runoff; therefore, minimal impact to the flow of the adjacent waterway occurs.

In 2005, the water was stored at the Lake Bronson site for a period of only 5 days because of a culvert connection failure that required a sooner-than-expected release. This connection failure could have been avoided if the culverts were permanently installed; however, because of the short-term nature of the project and the fact that the culvert modifications had to be removed after the trials, only a limited amount of sealant was used between the standpipe connection and the existing culvert. However, the 5-day storage was sufficient in reducing the peak flow in the coulee draining through the site by approximately 25%, as illustrated in Figure 56. The delay in the beginning of flow and the overall reduction in peak flow allowed the ice in the downstream

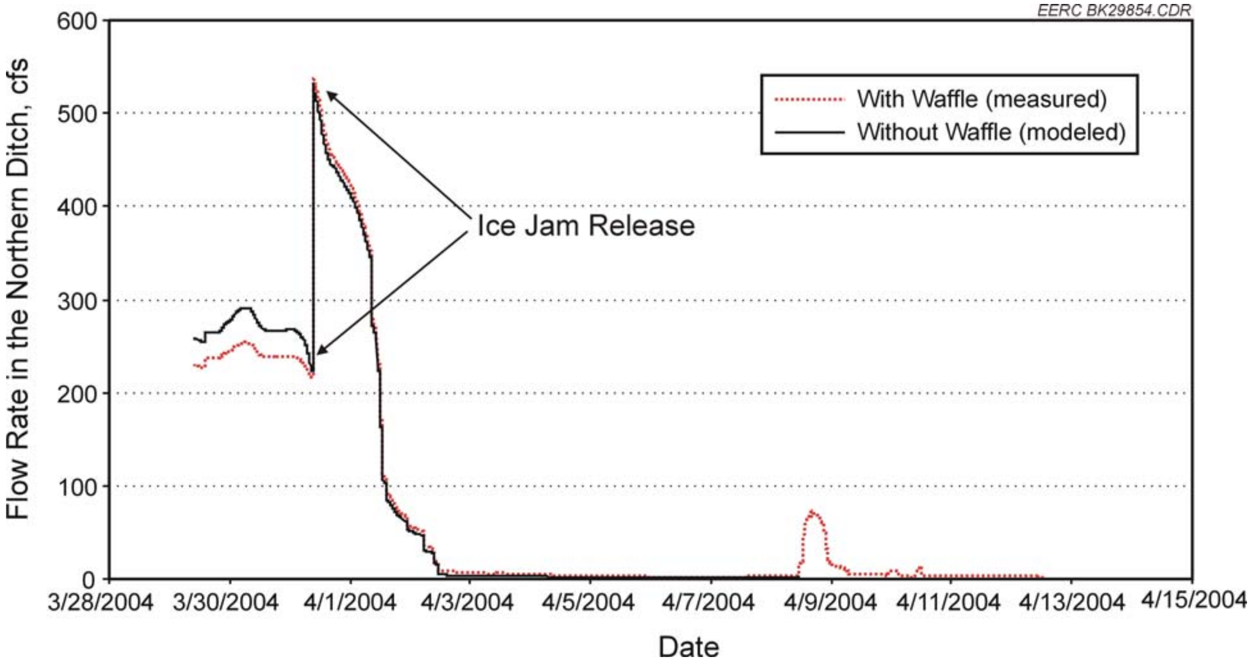


Figure 55. 2004 flow hydrograph at the Shelly site.

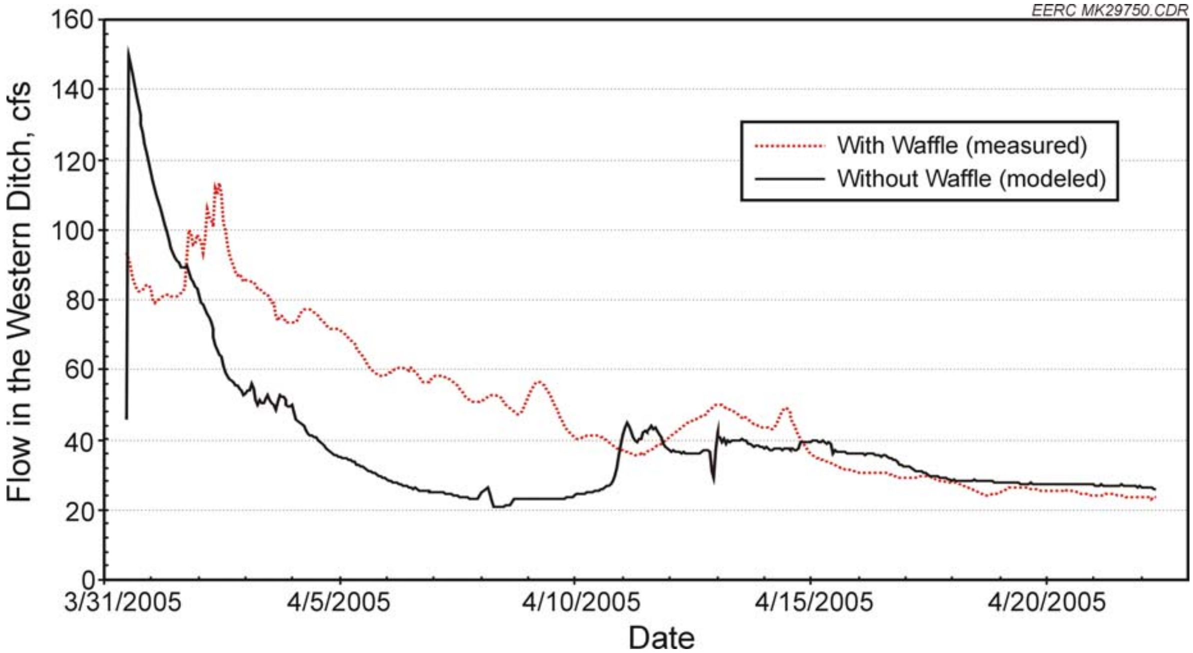


Figure 56. 2005 flow hydrograph at the Lake Bronson site.

portions of the coulee to break up and drain from the area prior to the main release. This delay in peak flows helped reduce the extent of flooding that normally occurs in that area, according to a nearby landowner.

In 2006 at the Lake Bronson site, the water was held back for the entire 14 days as planned. Figure 57 illustrates the flows measured within the coulee that drains the site. Again, the peak flows were reduced by approximately 25%–30%, and they remained lower than what could be expected under normal drainage conditions. The larger flow under Waffle conditions that occurs around April 13 is a result of initiating the water release to drain the field trial section. The flow, although elevated, is well below the peak flows observed at the onset of the melt and does not adversely impact the natural drainage.

The date of water release from each site was evaluated with respect to the peak discharge dates of adjacent tributaries and the Red River at the point nearest the respective tributary. Table 18 illustrates the date of release at each site and the dates of peak discharge for the associated tributary and Red River. The Gilby site is not included in the table because, at the landowner's request, the water was not released after storage.

The dates of water release for the trial sites were well beyond the peak flow dates on the tributaries and Red River for each year, with the exception of the Lake Bronson site. As previously mentioned, during the 2005 Lake Bronson field trial, the stored water had to be released approximately 9 days earlier than expected. Had the water been released on the anticipated date, it would have been well after the peak flows in the nearest tributary and in the Red River. In 2006, the water at the Lake Bronson site was released well after the peak flow occurred in the Two Rivers South Branch on April 4; however, the release date is approximately two days sooner than the peak flow that occurred on the Red River at Pembina. If the Waffle

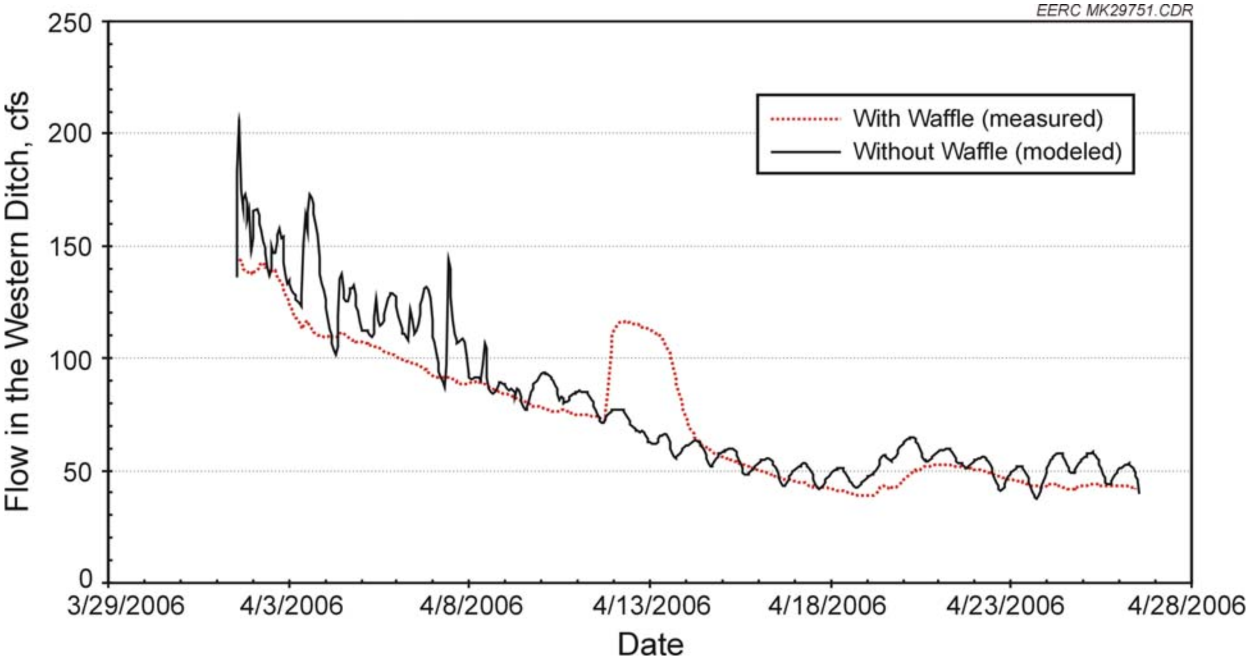


Figure 57. 2006 flow hydrograph at the Lake Bronson site.

Table 18. Waffle Storage Release Dates and Peak Flows of Associated Tributaries and Red River

	Demonstration Location	Release Date	Peak Flow – Tributary	Peak Flow – Red River
2004	Shelly	April 8	March 29 – Marsh River	March 29 – Halstad
2005	Lake Bronson	April 3	April 3 – Two Rivers S. Branch	April 9 – Pembina
	Agassiz	April 19	April 2 – Thief River	April 3 – Grand Forks
	Shelly	April 12	March 31 – Marsh River	March 31 – Halstad
2006	Lake Bronson	April 13	April 4 – Two Rivers S. Branch	April 15 – Pembina

concept were implemented on a larger scale in this portion of the RRB, this may not have been an ideal time for water release (depending on the travel time of the released water to the Red River) and, therefore, may have necessitated the need for a longer storage period. Ideally, the timing of water release from Waffle storage sites would be coordinated with peak flow dates for each flood event. Because flood crests occur later in the waterways located in the northern portion of the RRB, water storage later into the spring may be required for sections located within the northern portion of the RRB.

2.5.3.2 Evaporation and Infiltration Losses

Water loss through evaporation can be significant for areas of pooled water, especially if climatic conditions are favorable (i.e., windy, sunny, and warm). To understand the evaporation potential of the Waffle field trial sites in early spring, climatic data obtained from the meteorological stations were used to calculate average daily evaporation rates and total evaporation loss throughout the water storage periods. The equation used to calculate evaporation loss was developed by Campbell Scientific and is a modified version of the Penman–Monteith evapotranspiration equation. The equation is based on factors such as wind velocity, solar radiation, temperature, barometric pressure, and humidity. The result is provided in inches per day, which was then converted into volume by taking the surface area of water into account.

Infiltration can also play a significant role in temporary water storage sites. To estimate infiltration amounts at the trial sites, several variables were considered, including soil moisture levels prior to water storage, soil porosity, location of frost within the soil profile, depth of stored water, and aerial extent of water storage.

Table 19 illustrates the estimated total evaporation and infiltration losses for the Shelly site in 2004 and all four sites in 2005. The estimated daily evaporation rates ranged from 0.18 to 4.00 acre-ft. As seen in Table 19, when compared to total released storage volume, the volume of water retained on the site because of infiltration and evaporative losses was quite significant, equivalent to more than 50% of the total released volume in some cases. This is important not only for helping to reduce the total volume of springtime flood events, but also because infiltration is the primary mechanism to recharge local groundwater supplies. Infiltration also increases soil moisture, which could benefit crops during years without sufficient precipitation in the growing season.

Table 19. Evaporation and Infiltration Estimates for Each Demonstration Location

Location	Year	Storage Period, days	Estimated Evaporation, acre-ft	Estimated Infiltration, acre-ft	Water Volume Released, acre-ft	Total Volume Retained, acre-ft
Shelly	2004	14	19	61	127	207
Shelly	2005	13	7	54	133	194
Lake Bronson	2005	5	6	12	147	165
Agassiz Refuge	2005	28	40	72	45	157
Gilby	2005	45	75	68	–	–

2.5.3.2 Soil Temperature

Soil temperature data were collected at the Shelly site in 2004, the Lake Bronson and Agassiz Wildlife Refuge sites in 2005, and the Lake Bronson site in 2006. These data provided valuable insight into the progression of the thaw of frozen soils on both the flooded and nonflooded portions of the trial sites.

In 2004, water was stored on the soils of the Shelly site for 14 consecutive days. The frost in the soils underlying the flooded areas showed a more rapid and consistent rate of thaw than the frost within the nonflooded soils, as is seen in Figure 58. This phenomenon was likely due to the capacity of the overlying water to insulate the soils from freezing nighttime temperatures, as well as increased soil moisture throughout the thawed soil profile. The additional soil moisture was in contact with the frost boundary and provided the heat energy required to maintain a continual thaw progression. The nonflooded zone, however, did not experience the additional soil moisture or the insulating capacity of the overlying pool of water and, therefore, was more susceptible to freezing temperatures during the night. As seen in Figure 58, the thaw progression rate showed a lag effect in the nonflooded soils between the dates of April 1 and April 14, which is consistent with a period of below-freezing air temperatures. The thaw progression results of the study are indicative of a top-to-bottom thawing effect, which, according to the U.S. Forest Service, is the expected trend in the climatic region of the Shelly field site.

At both the Lake Bronson and Agassiz Wildlife Refuge sites in 2005, the stored water appeared to delay the beginning of frost removal by approximately 3 days. However, at both locations, once frost removal began, the rate at which it was removed occurred moderately faster in areas with stored water (Figures 59 and 60). Again, this phenomenon is likely due to the overlying water and the increased soil moisture throughout the soil profile.

In 2006, at the Lake Bronson site, the beginning of frost removal in the flooded portion of the site was almost a week ahead of the nonflooded area. As can be seen in Figure 61, by April 10, the frost had thawed nearly 4 more inches in the flooded area than in the nonflooded area. Although the rate of removal decreased somewhat on the flooded area, the frost was removed to a depth of 24 inches approximately 3 days ahead of the nonflooded area. The difference in frost removal rates at the Lake Bronson site between 2005 and 2006 is likely due to

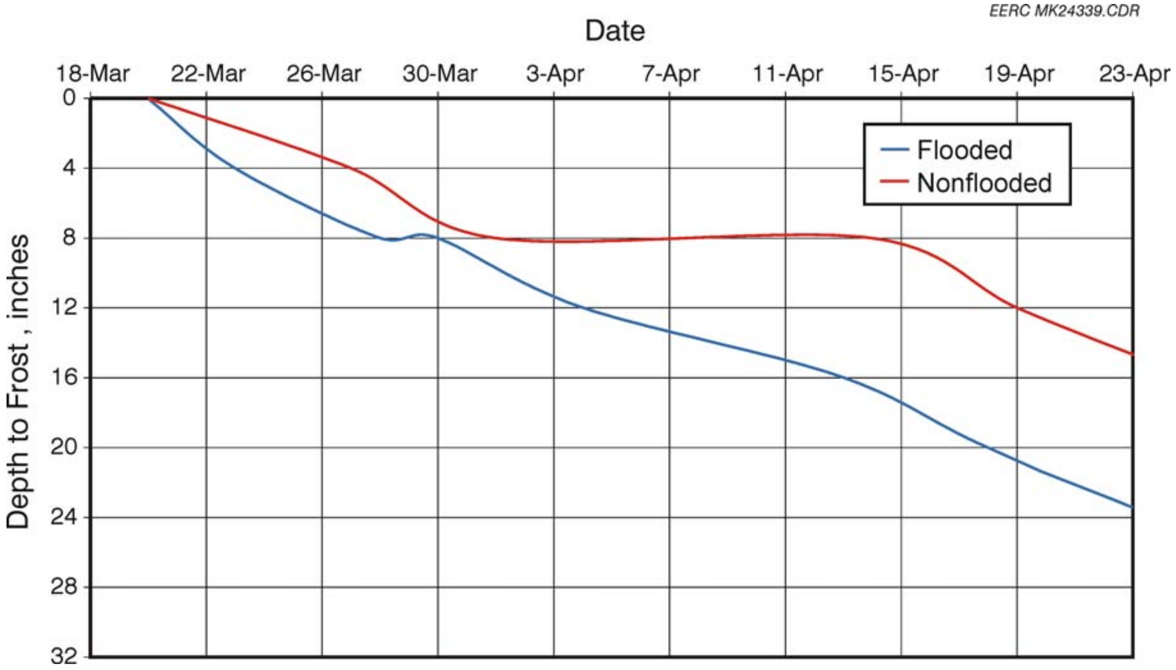


Figure 58. 2004 frost profile for the flooded and nonflooded zones at the Shelly site.

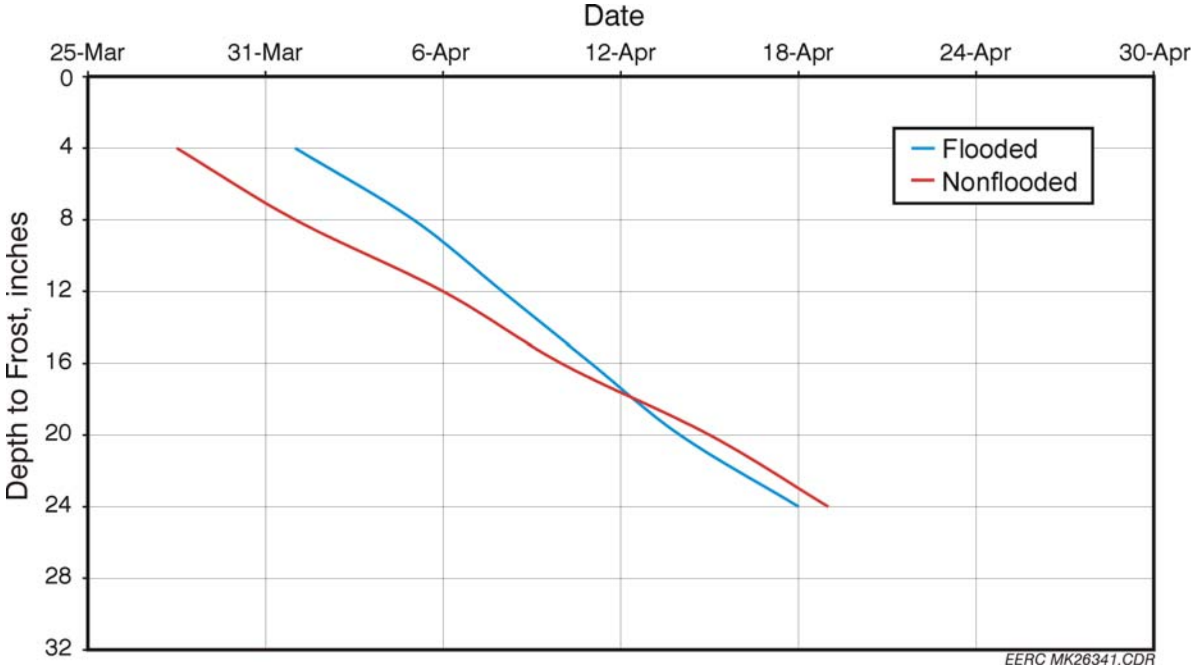


Figure 59. 2005 frost profile for the flooded and nonflooded zones at the Lake Bronson site.

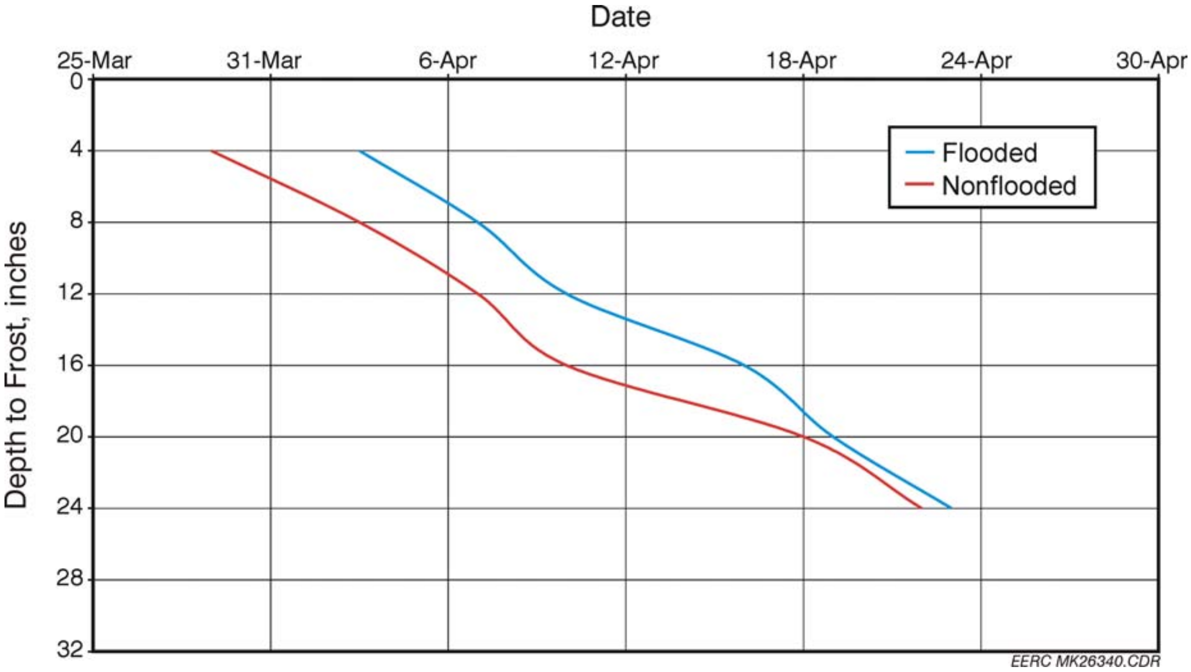


Figure 60. 2005 frost profile for the flooded and nonflooded zones at the Agassiz Refuge site.

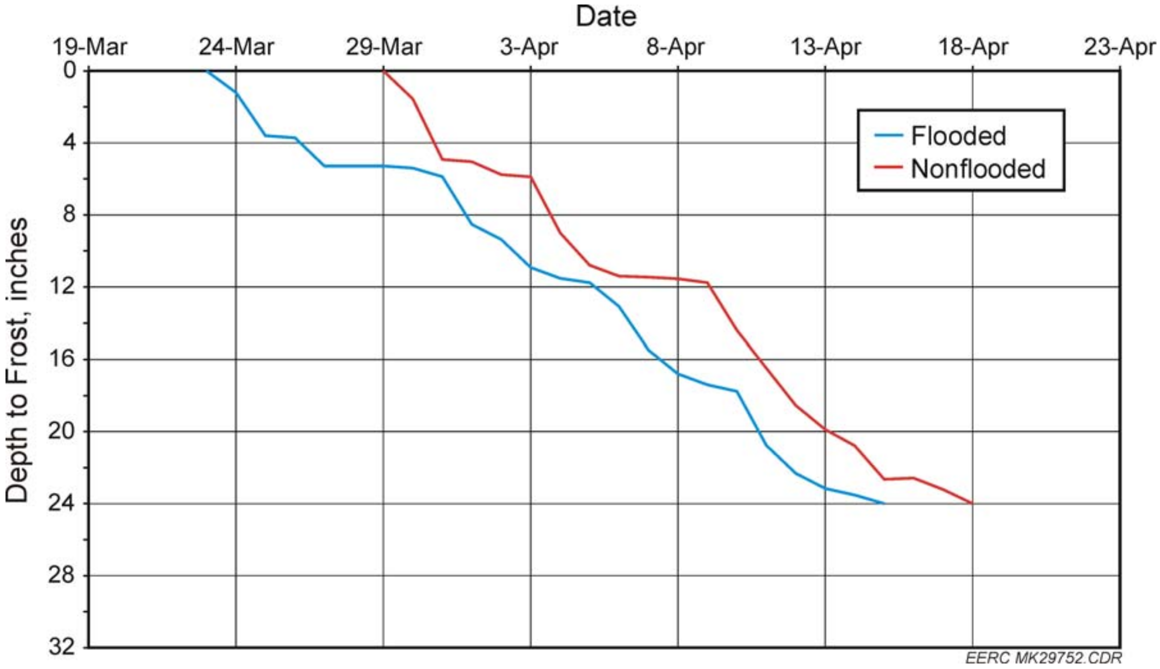


Figure 61. 2006 frost profile for the flooded and nonflooded zones at the Lake Bronson site.

a change in sensor position. The sensor located in the nonflooded portion of the site was moved further away from the water storage area during 2006.

2.5.3.3 Soil Moisture

As expected, there was a noticeable difference in soil moisture levels between flooded and nonflooded portions of the trial sites, as shown in Figure 62. In 2004, at the Shelly site, a slight increase in moisture content at the very onset of the thaw was observed in both the flooded and nonflooded soils near the surface, because of the melting of ice crystals within the soil matrix. However, over time, the soils not covered by stored water exhibited a gradual decrease in moisture content in the upper layers. In contrast, flooded soils maintained a higher level of moisture content longer into the growing season. This may moderately delay planting; however, it may also provide benefits to crop production, especially in periods of drought.

In 2005, soil moisture was monitored at both the Lake Bronson and the Agassiz Wildlife Refuge site. Again, the soil moisture levels on the flooded portions of the sites were greater during the melt and remained at higher levels longer into the growing season. Figures 63 and 64 illustrate the difference in moisture levels at a depth of 8 inches at both the Lake Bronson and Agassiz Refuge sites, respectively, during the 2005 demonstration. The differences are illustrated for both the flooded and nonflooded areas of the sites.

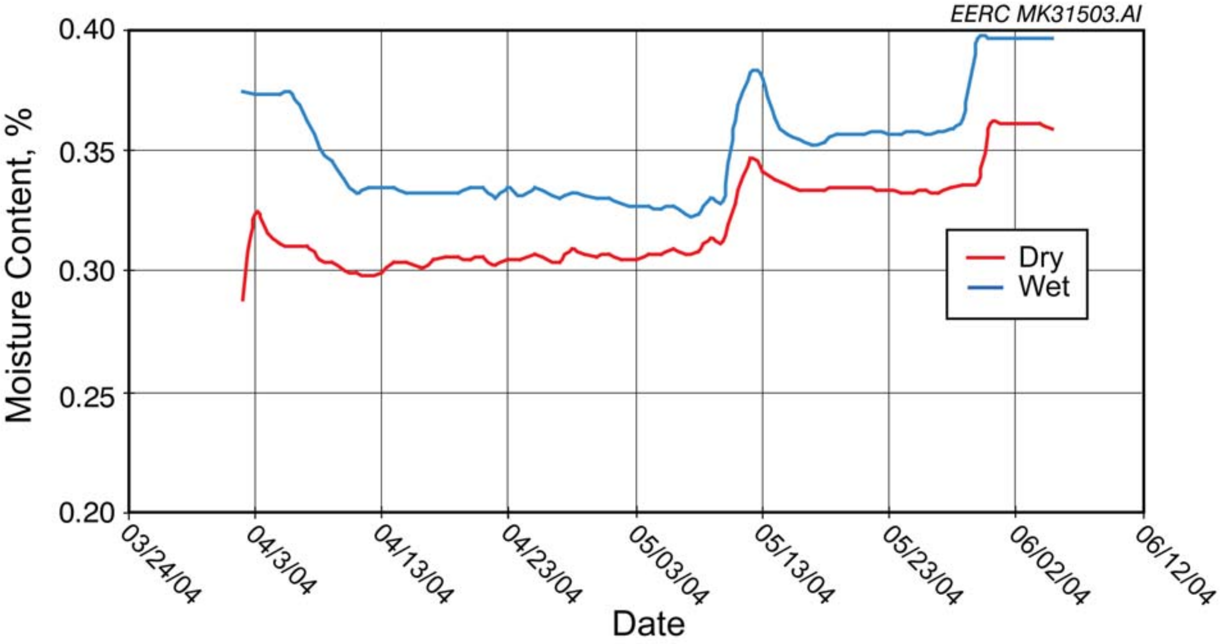


Figure 62. 2004 Shelly site soil moisture.

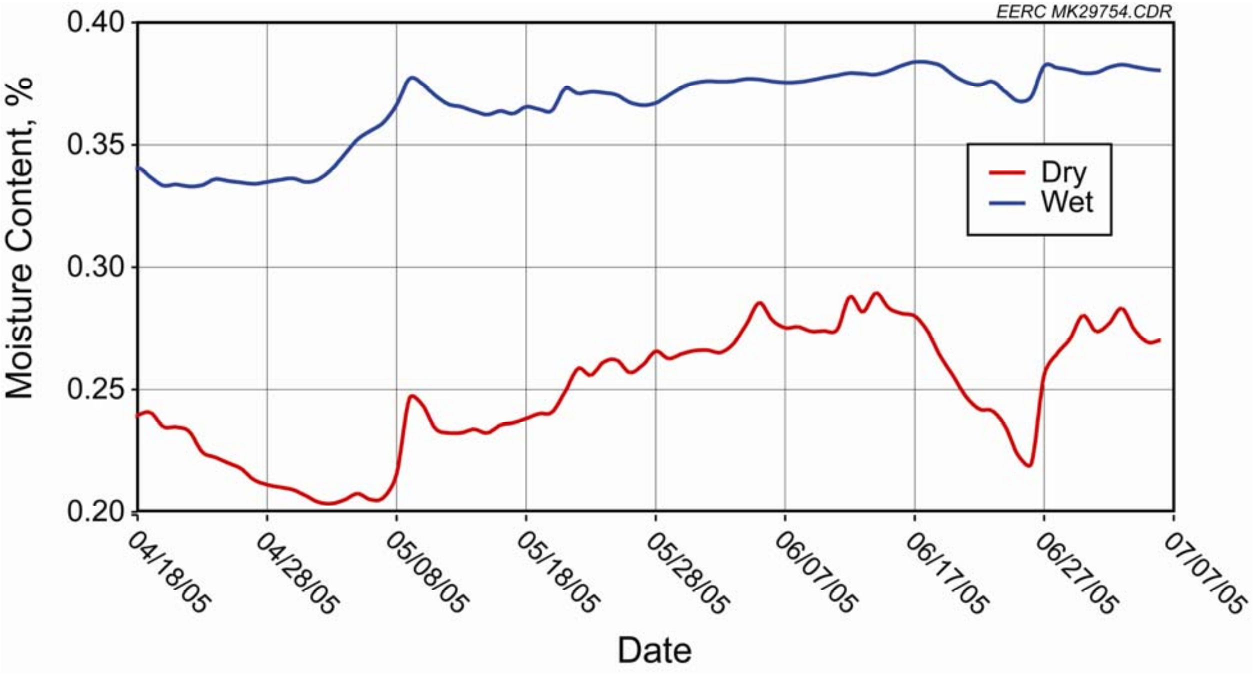


Figure 63. 2005 soil moisture comparisons of flooded and nonflooded zones at the Lake Bronson site at a depth of 8 inches.

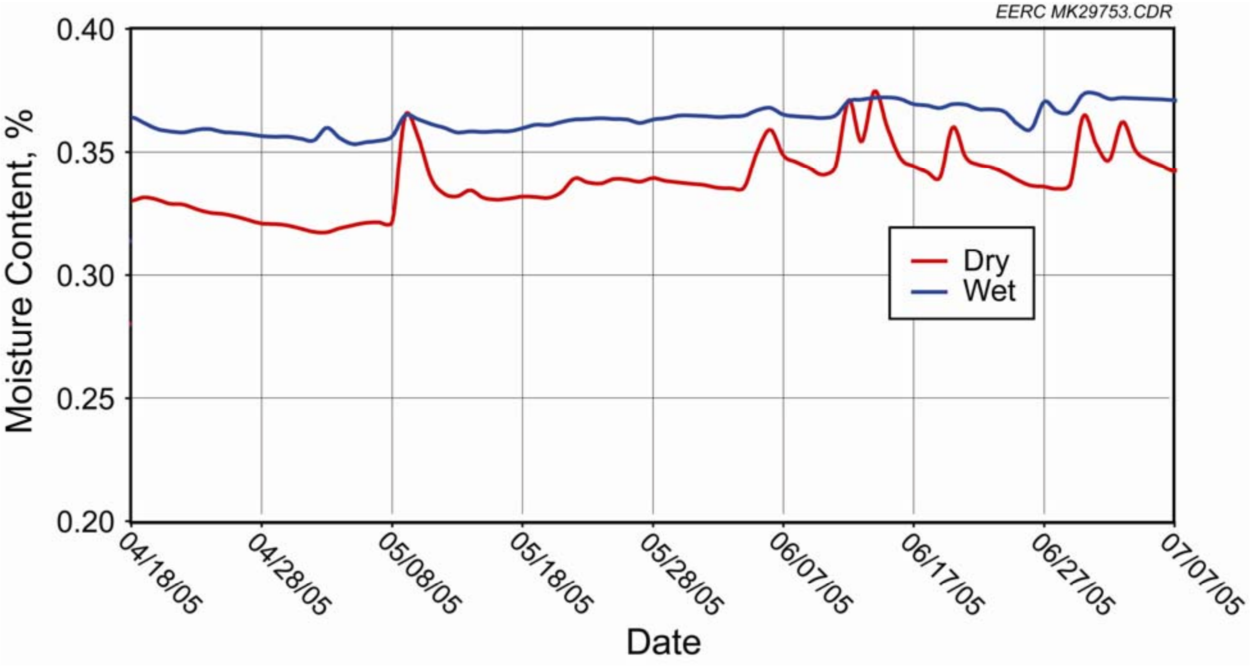


Figure 64. 2005 soil moisture comparisons of flooded and nonflooded zones at the Agassiz site at a depth of 8 inches.

2.5.3.4 Water Quality Analysis

Shelly Site: Water quality data were collected and analyzed from the Shelly site during both the 2004 and 2005 demonstrations. A background snowpack sample was obtained, and several samples of the melt water from the section and adjacent ditches were taken at various times during the spring. The water samples in adjacent ditches were collected upgradient of the site during peak flow conditions, while samples from the site itself were collected after 8 and 14 days of water storage. The samples from the ditch downgradient were taken during the release of the water from the site. Results are shown in Tables 20 and 21. Each table contains a sample collection location with the corresponding number illustrated on its plan view of the site.

In both years, the salts that readily dissolve in water; their attendant constituents such as chloride, sulfate, sodium, magnesium, and bicarbonate; and corresponding parameters such as hardness, conductivity, and alkalinity were moderately higher in samples taken from the adjacent ditches upgradient of the site. These elevated concentrations may have been the result of salt deposits left behind in the ditches after evaporation of water from previous runoff events. The analytical results for the water stored within the section indicate no significant difference in chemical constituents between the 8- and 14-day storage scenarios in either year, suggesting the length of storage does not impact the water chemistry. No pesticides or herbicides were detected in any samples for either year.

Agassiz Wildlife Refuge Site: Water quality sampling at this site was also conducted during the spring 2005 demonstration. Four samples were obtained at this site: one sample of the water upgradient in the adjacent judicial ditch and three samples obtained within the section at storage periods of 7, 14, and 21 days. Analytical results are shown in Table 22. Although a few of the parameters such as calcium, magnesium, sulfate, total inorganic carbon, alkalinity, and bicarbonate showed a slightly lower concentration in the 7-day storage scenario when compared to the 14- and 21-day storage scenarios, there was virtually no difference between the stored water and the water in the adjacent judicial ditch. There were no herbicides or pesticides detected in any samples.

Lake Bronson Site: Water quality sampling was conducted during the 2005 Lake Bronson field trial. Only three samples were obtained at this site because of the early release of the stored water. After 5 days of storage, a sample was taken of the water coming into the site from the upstream drainage area, and another sample was taken of the water that had been stored on the site. The third sample was taken from the site's snowpack to serve as a baseline for comparison with water quality after storage. The analytical results are shown in Table 23. The water quality of the two samples taken from the site and from the water coming into the site were very similar, with just slightly higher levels of total dissolved solids, hardness, and bicarbonate (as HCO_3) in the upgradient water. No pesticides or herbicides were detected in either of the samples, and the overall quality of water in the drainage system did not appear to be adversely impacted by the 5-day storage period.

Gilby Site: A total of five water quality samples were collected at the Gilby site in 2005. Two samples were collected in ditches adjacent to and upgradient of the section, and three samples were collected within the section at storage periods of 7, 17, and 21 days. Analytical results are shown in Table 24. Certain parameters such as chloride, sulfate, conductivity,

Table 20. 2004 Water Quality Results (Shelly site)

	Melted Snowpack	North Upgradient	8-day Storage North	14-day Storage North	North Down-gradient	South Upgradient	14-day Storage South	South Down-gradient	Units	Reporting Limit
Sample Locations	–	1	2	3	4	5	6	7		
Redox Potential	29	192	226	211	193	200	195	187	mV	
pH	6.8	8.3	7.7	7.8	7.8	7.7	7.8	7.9	s.u.	
Conductivity	16	852	312	318	319	871	303	330	µS/cm	1
Turbidity	30.6	3.6	52.0	40.0	62.0	10.0	60.0	68.0	NTU	0.02
Total Suspended Solids at 105°C	69	BRL	41	73	108	12	116	128	mg/L	10
Total Dissolved Solids at 180°C	12	615	189	221	219	661	230	236	mg/L	10
Total Alkalinity as $CaCO_3$	6	259	145	157	162	261	148	152	mg/L	2
Bicarbonate Alkalinity as HCO_3	8	306	177	192	197	319	181	186	mg/L	2
Carbonate Alkalinity as CO_3	BRL[1]	5	BRL	BRL	BRL	BRL	BRL	BRL	mg/L	1
Hydroxide Alkalinity as OH	BRL	BRL	BRL	BRL	BRL	BRL	BRL	BRL	mg/L	1
Chloride	BRL	12	2	2	2	4	2	2	mg/L	1
Sulfate	BRL	267	17	17	18	285	21	26	mg/L	1
Sodium Adsorption Ratio (SAR)	BRL	0.62	0.13	0.13	0.13	0.45	0.13	0.14		0.01
Hardness as $CaCO_3$	4	453	159	164	160	488	165	170	mg/L	1
Biochemical Oxygen Demand	BRL	BRL	BRL	4	4	BRL	4	4	mg/L	4
Chemical Oxygen Demand	BRL	26	28	25	25	31	24	22	mg/L	1
Total Organic Carbon	1.0	14.4	12.1	11.2	13.1	13.4	12.1	10.9	mg/L	0.5
Total Inorganic Carbon	1.7	60.8	NA[2]	38.7	37.8	62.0	36.2	35.8	mg/L	0.5
Nitrogen, ammonia as N	0.2	BRL	BRL	BRL	BRL	0.2	BRL	BRL	mg/L	0.1
Nitrogen, nitrite as N	BRL	BRL	0.11	0.10	0.10	0.09	0.11	0.10	mg/L	0.05
Nitrogen, nitrate	0.24	0.09	1.32	0.81	0.75	1.32	1.80	1.67	mg/L	0.05
Nitrogen, nitrate + nitrite, as N	0.24	0.09	1.43	0.91	0.85	1.41	1.91	1.77	mg/L	0.05
Nitrogen, Kjeldahl, total as N	1.0	2.0	2.0	1.2	1.6	2.0	2.2	1.2	mg/L	0.5
Phosphorus, total as P	0.05	0.14	0.10	0.09	0.15	0.30	0.21	0.27	mg/L	0.01
Calcium	BRL	81	36	37	36	96	38	38	mg/L	1
Magnesium	BRL	61	17	17	17	60	17	18	mg/L	1
Potassium	BRL	11	10	11	11	12	8	9	mg/L	1
Sodium	BRL	30	4	4	4	23	4	4	mg/L	1
Iron, total	0.05	0.20	1.83	2.73	3.70	0.37	4.59	4.94	mg/L	0.03
Mercury, total	BRL	BRL	BRL	BRL	BRL	BRL	BRL	BRL	mg/L	0.05
Pesticides,[3] total	BRL	BRL	BRL	BRL	BRL	BRL	BRL	BRL	µg/L	1
Herbicides,[4] total	BRL	BRL	BRL	BRL	BRL	BRL	BRL	BRL	µg/L	2.5

[1] Below reporting limit.

[2] Not analyzed.

[3] Alachlor, Aldrin, Aroclor, total polychlorinated biphenyls (PCBs), Atrazine, Chlordane, Dieldrin, Endrin, Heptachlor, hexachlorobenzene, hexachlorocyclopentadiene, Methoxychlor, Nonaclor, Simazine, Toxaphene, and Trifluralin.

[4] Dalapon, Dicamba, Dinoseb, and pentachlorophenol.

Table 21. 2005 Water Quality Results (Shelly site)

	Snowpack Melt	Upgradient North	8-day Storage North	14-day Storage North	Upgradient South	8-day Storage South	Units	Method Reporting Limit
Sample Locations	–	1	2	3	5	6		
Redox Potential	305	236	232	181	232	244	mV	
pH	6.29	7.50	6.89	6.86	7.59	7.38	s.u.	
Conductivity	12.7	387	227	255	563	273	µS/cm	1
Turbidity	13.3	3.53	5.74	3.73	2.74	17.4	NTU	0.02
Total Suspended Solids at 105°C	79	17	13	18	14	36	mg/L	10
Total Dissolved Solids at 180°C	32	222	212	256	356	206	mg/L	10
Total Alkalinity as $CaCO_3$	3.92	177	130	141	222	114	mg/L	2
Bicarbonate as HCO_3	4.78	216	159	172	271	139	mg/L	2
Carbonate as CO_3	BRL[1]	BRL	BRL	BRL	BRL	BRL	mg/L	1
Hydroxide as OH	BRL	BRL	BRL	BRL	BRL	BRL	mg/L	1
Chloride	BRL	9.6	4.6	4.9	6.7	3.2	mg/L	1
Sulfate	BRL	52.0	8.1	13.7	130	28.9	mg/L	1
SAR	BRL	0.32	0.05	0.07	0.39	0.15		0.01
Hardness as $CaCO_3$	4	216	117	145	310	149	mg/L	1
Biochemical Oxygen Demand	BRL	BRL	18.6	<6	BRL	8.1	mg/L	6
Chemical Oxygen Demand	BRL	35.6	59.5	54.1	52.4	32.5	mg/L	5
Total Organic Carbon	BRL	15.3	26.6	23.5	22.6	13.4	mg/L	1
Total Inorganic Carbon	BRL	40.1	30.0	35.6	44.0	27.6	mg/L	1
Nitrogen, ammonia as N	0.28	BRL	BRL	BRL	BRL	BRL	mg/L	0.1
Nitrogen, nitrite as N	BRL	BRL	BRL	BRL	BRL	BRL	mg/L	1
Nitrogen, nitrate	BRL	5.8	BRL	BRL	9.3	14.5	mg/L	1
Nitrogen, Kjeldahl, total as N	1.1	1.4	3.1	3.0	1.8	2.2	mg/L	0.5
Phosphorus, total as P	BRL	BRL	BRL	BRL	BRL	BRL	mg/L	0.3
Calcium	1.51	41.7	24.6	30.5	60.0	32.6	mg/L	1
Magnesium	0.25	27.1	13.4	16.7	38.9	16.4	mg/L	1
Potassium	BRL	10.0	21.7	23.7	9.5	13.0	mg/L	1
Sodium	BRL	10.8	1.2	1.8	15.7	4.2	mg/L	1
Iron, total	0.013	0.013	BRL	0.099	BRL	BRL	mg/L	0.01
Mercury, total	BRL	BRL	BRL	BRL	BRL	BRL	µg/L	0.01
Pesticides,[2] total	BRL	BRL	BRL	BRL	BRL	BRL	µg/L	1
Herbicides,[3] total	BRL	BRL	BRL	BRL	BRL	BRL	µg/L	2.5

[1] Below reporting limit.

[2] Alachlor, Aldrin/Dieldrin, Aroclor, total PCBs, Atrazine; Chlordane, Endrin, Heptachlor, hexachlorobenzene, hexachlorocyclopentadiene, Methoxychlor, Nonaclor, Simazine, Toxaphene, and Trifluralin.

[3] Dalapon, Dicamba, Dinoseb, and pentachlorophenol.

Table 22. 2005 Water Quality Results (Agassiz Wildlife Refuge site)

	Upgradient	7-day Storage	14-day Storage	21-day Storage	Units	Method Reporting Limit
Sample Locations	1	2	3	4		
Redox Potential	235	234	230	189	mV	
pH	6.99	7.04	7.02	7.13	s.u.	
Conductivity	309	148	324	316	µS/cm	1
Turbidity	3.90	1.45	2.26	2.21	NTU	0.02
Total Suspended Solids at 105°C	BRL[1]	14	BRL	BRL	mg/L	10
Total Dissolved Solids at 180°C	166	44.0	378	276	mg/L	10
Total Alkalinity as $CaCO_3$	77.6	46.4	89.1	93.1	mg/L	2
Bicarbonate as HCO_3	94.7	56.7	109.0	114.0	mg/L	2
Carbonate as CO_3	BRL	BRL	BRL	BRL	mg/L	1
Hydroxide as OH	BRL	BRL	BRL	BRL	mg/L	1
Chloride	5.8	8.6	5.0	10.0	mg/L	1
Sulfate	87.7	12.5	95.6	68.8	mg/L	1
SAR	0.06	0.02	0.06	0.02		0.01
Hardness as $CaCO_3$	160	50	190	159	mg/L	1
Biochemical Oxygen Demand	BRL	6.9	BRL	BRL	mg/L	6
Chemical Oxygen Demand	37.9	49.1	28.9	48.5	mg/L	5
Total Organic Carbon	16.0	20.9	11.9	21.1	mg/L	1
Total Inorganic Carbon	17.7	13.0	25.5	29.3	mg/L	1
Nitrogen, ammonia as N	0.34	0.31	BRL	BRL	mg/L	0.1
Nitrogen, nitrite as N	BRL	BRL	BRL	BRL	mg/L	1
Nitrogen, nitrate	3.3	1.4	BRL	BRL	mg/L	1
Nitrogen, Kjeldahl, total as N	1.9	2.1	1.5	2.4	mg/L	0.5
Phosphorus, total as P	BRL	BRL	BRL	BRL	mg/L	0.3
Calcium	42.3	14.4	51.3	44.4	mg/L	1
Magnesium	13.2	3.53	15.0	11.8	mg/L	1
Potassium	5.9	20.1	6.0	25.0	mg/L	1
Sodium	1.9	BRL	1.8	BRL	mg/L	1
Iron, total	0.362	0.022	0.144	0.137	mg/L	0.01
Mercury, total	BRL	BRL	BRL	BRL	µg/L	0.01
Pesticides,[2] total	BRL	BRL	BRL	BRL	µg/L	1
Herbicides,[3] total	BRL	BRL	BRL	BRL	µg/L	2.5

[1] Below reporting limit.

[2] Alachlor, Aldrin/Dieldrin, Aroclor, total PCBs, Atrazine; Chlordane, Endrin, Heptachlor, hexachlorobenzene, hexachlorocyclopentadiene, Methoxychlor, Nonaclor, Simazine, Toxaphene, and Trifluralin.

[3] Dalapon, Dicamba, Dinoseb, and pentachlorophenol.

Table 23. 2005 Water Quality Results (Lake Bronson site)

	Melted Snowpack	Upgradient	5-day Storage	Units	Method Reporting Limit
Sample Locations	–	1	2		
Redox Potential	NA[1]	178	188	mV	
pH	6.31	7.68	7.10	s.u.	
Conductivity	10.6	314	213	µS/cm	1
Turbidity	25.3	2.36	2.42	NTU	0.02
Total Suspended Solids at 105°C	31	BRL[2]	BRL	mg/L	10
Total Dissolved Solids at 180°C	39.0	136.0	98.0	mg/L	10
Alkalinity as $CaCO_3$	2.98	191	126	mg/L	2
Bicarbonate as HCO_3	3.64	233	154	mg/L	2
Carbonate as CO_3	BRL	BRL	BRL	mg/L	1
Hydroxide as OH	BRL	BRL	BRL	mg/L	1
Chloride	BRL	3.0	8.1	mg/L	1
Sulfate	BRL	BRL	6.5	mg/L	1
SAR	BRL	0.11	0.10		0.01
Hardness as $CaCO_3$	3	193	123	mg/L	1
Biochemical Oxygen Demand	BRL	BRL	BRL	mg/L	6
Chemical Oxygen Demand	BRL	32.9	36.8	mg/L	5
Total Organic Carbon	1.7	14.1	15.9	mg/L	1
Total Inorganic Carbon	1.5	43.7	26.6	mg/L	1
Nitrogen, ammonia as N	0.30	BRL	BRL	mg/L	0.1
Nitrogen, nitrite as N	BRL	BRL	BRL	mg/L	1
Nitrogen, nitrate	BRL	BRL	BRL	mg/L	1
Nitrogen, Kjeldahl, total as N	NA	1.0	1.6	mg/L	0.5
Phosphorus, total as P	BRL	BRL	BRL	mg/L	0.3
Calcium	1.27	42.0	27.5	mg/L	1
Magnesium	0.083	21.3	12.8	mg/L	1
Potassium	BRL	4.2	7.8	mg/L	1
Sodium	BRL	3.6	2.5	mg/L	1
Iron, total	BRL	0.111	0.020	mg/L	0.01
Mercury, total	BRL	BRL	BRL	µg/L	0.01
Pesticides,[3] total	BRL	BRL	BRL	µg/L	1
Herbicides,[4] total	BRL	BRL	BRL	µg/L	2.5

[1] Not applicable.

[2] Below reporting limit.

[3] Alachlor, Aldrin/Dieldrin, Aroclor, total PCBs, Atrazine, Chlordane, Endrin, Heptachlor, hexachlorobenzene, hexachlorocyclopentadiene, Methoxychlor, Nonaclor, Simazine, Toxaphene, and Trifluralin.

[4] Dalapon, Dicamba, Dinoseb, pentachlorophenol.

Table 24. 2005 Water Quality Results (Gilby site)

	Upgradient SE	Upgradient NW	7-day Storage	17-day Storage	21-day Storage	Units	Method Reporting Limit
Sample Locations	1	2	3	4	5		
Redox Potential	231	228	225	211	197	mV	
pH	7.63	7.5	7.13	7.02	7.31	s.u.	
Conductivity	880	647	301	488	639	µS/cm	1
Turbidity	1.72	1.81	2.30	5.09	2.00	NTU	0.02
Total Suspended Solids at 105°C	17	BRL[1]	BRL	BRL	BRL	mg/L	10
Total Dissolved Solids at 180°C	626	472	136	512	554	mg/L	10
Alkalinity as $CaCO_3$	149	134	87.5	114	142	mg/L	2
Bicarbonate as HCO_3	182	164	107	139	173	mg/L	2
Carbonate as CO_3	BRL	BRL	BRL	BRL	BRL	mg/L	1
Hydroxide as OH	BRL	BRL	BRL	BRL	BRL	mg/L	1
Chloride	149	65.2	18.5	44.1	66.2	mg/L	1
Sulfate	189	167	62.9	117	169	mg/L	1
SAR	1.01	0.79	0.29	0.49	0.65		0.01
Hardness as $CaCO_3$	401	296	146	234	334	mg/L	1
Biochemical Oxygen Demand	BRL	BRL	6.3	BRL	BRL	mg/L	6
Chemical Oxygen Demand	53.2	51.4	52.8	55.6	64.8	mg/L	5
Total Organic Carbon	23.3	22.4	23.4	26.9	28.3	mg/L	1
Total Inorganic Carbon	33.9	29.6	18.5	34.3	30.1	mg/L	1
Nitrogen, ammonia as N	BRL	BRL	BRL	BRL	BRL	mg/L	0.1
Nitrogen, nitrite as N	BRL	BRL	BRL	BRL	BRL	mg/L	1
Nitrogen, nitrate	BRL	2.2	BRL	BRL	BRL	mg/L	1
Nitrogen, Kjeldahl, total as N	2.0	1.8	1.5	1.8	2.0	mg/L	0.5
Phosphorus, total as P	BRL	BRL	BRL	BRL	BRL	mg/L	0.3
Calcium	95.9	69.7	39.2	62.6	88.2	mg/L	1
Magnesium	39.3	29.6	11.7	18.9	27.7	mg/L	1
Potassium	12.1	13.8	11.1	12.5	15.8	mg/L	1
Sodium	46.6	31.1	8.1	17.2	27.2	mg/L	1
Iron, total	0.040	BRL	0.016	0.019	0.017	mg/L	0.01
Mercury, total	BRL	BRL	BRL	BRL	BRL	µg/L	0.01
Pesticides,[2] total	BRL	BRL	BRL	BRL	BRL	µg/L	1
Herbicides,[3] total	BRL	BRL	BRL	BRL	BRL	µg/L	2.5

---

[1] Below reporting limit.

[2] Alachlor, Aldrin/Dieldrin, Aroclor, total PCBs, Atrazine, Chlordane, Endrin, Heptachlor, hexachlorobenzene, hexachlorocyclopentadiene, Methoxychlor, Nonaclor, Simazine, Toxaphene, and Trifluralin.

[3] Dalapon, Dicamba, Dinoseb, and pentachlorophenol.

alkalinity, bicarbonate, calcium, magnesium, and sodium exhibited a consistent increase as a function of storage duration. However, the water quality within the storage section never exceeded that of the adjacent drainage ditches.

Overall, at all four demonstration sites, no adverse effects to water quality were apparent from the storage of water on either agricultural or CRP lands during the 5- to 21-day storage scenarios. The blank and duplicate samples obtained for quality control purposes were within 5%–10% variability.

2.5.3.5 Soil Chemistry Analysis

Soil chemistry is an important factor in the agricultural industry, which is the backbone of the region's economy. As part of the Waffle field trials, it was important to understand how the extended storage of water on soils would affect soil chemistry from an agricultural perspective. Two sites were evaluated with respect to soil chemistry: the Shelly site in Minnesota and the Gilby site in North Dakota. The Shelly site is utilized as agricultural land and was evaluated for two consecutive seasons in 2004 and 2005. The Gilby site, although not currently in agricultural use, was also evaluated to assess any changes in soil chemistry in regional groundwater discharge areas. Key soil constituents considered important in agriculture are discussed in this section, with the detailed soil chemistry results listed in Appendix D.

In general, phosphorus concentrations during each field trial exhibited limited changes between the fall of 2003 and 2004 and again in the late springs/early summer of 2004 and 2005 analyses. Figures 65 and 66 illustrate the fall and spring phosphorus concentrations in both the flooded and nonflooded areas of the monitored sites. The Shelly site exhibited little change in phosphorus concentration in both 2004 and 2005 in the areas where water was stored. In the 2004 demonstration, phosphorus concentrations averaged 8.0 ppm in both the fall and spring analyses. In the 2005 demonstration, the average concentration was 10.0 ppm in the fall and 10.3 ppm in the spring, with a standard deviation of 1.3 ppm. In the area where water was not stored, there is a slight increase from 6.0 to 7.5 ppm in the average phosphorus concentrations from fall to spring during the 2004 demonstration and a decrease from 5.0 to 4.0 during the 2005 demonstration. The standard deviation for both of these areas for each year was 0.8 ppm.

The Gilby site exhibited the greatest reduction in phosphorus from 15.5 ppm in the fall to 1.0 ppm in the spring in the soils that were exposed to the stored water. Unlike many of the other constituents, a concomitant increase in phosphorus was not observed in the overlying water. This site also exhibited a similar but smaller decrease in phosphorus from 7.3 to 5.0 ppm in the soils not subjected to water storage.

Nitrate in the soil samples taken from 0 to 6 inches depth illustrated similar concentrations for both the flooded and nonflooded areas of the Shelly and Gilby sites from the fall of 2004 to the spring of 2005. However, during the 2004 Shelly trial, there was a change in nitrate concentrations from the fall to the spring in both the flooded and nonflooded areas that cannot be attributed to soil heterogeneity (Figures 67 and 68). The flooded portion of the site exhibited a

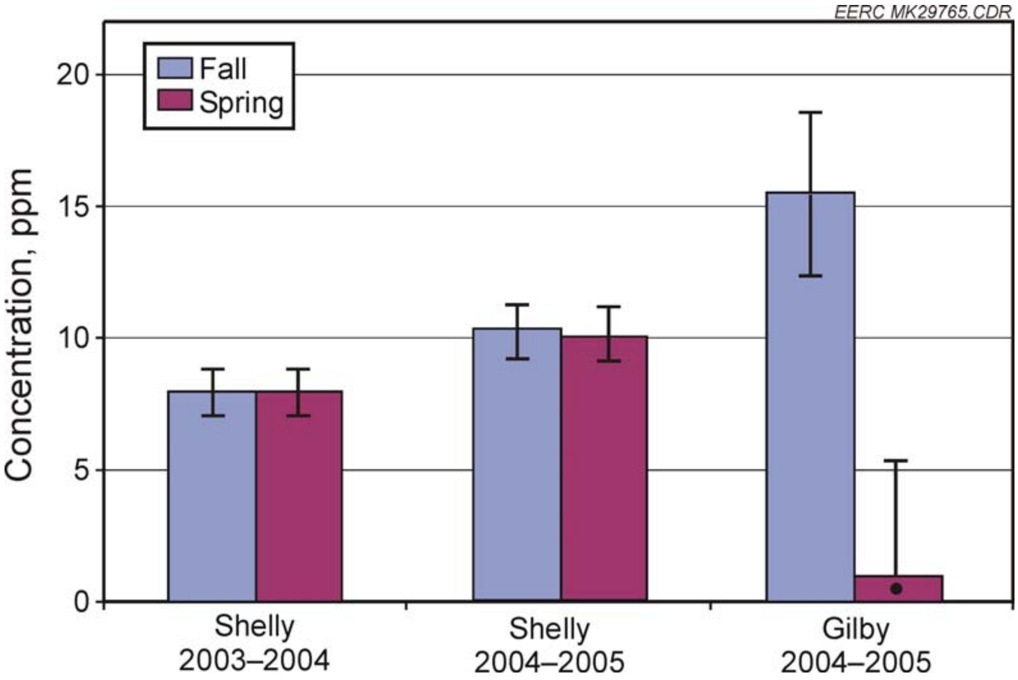


Figure 65. Fall and spring phosphorus content in flooded areas.

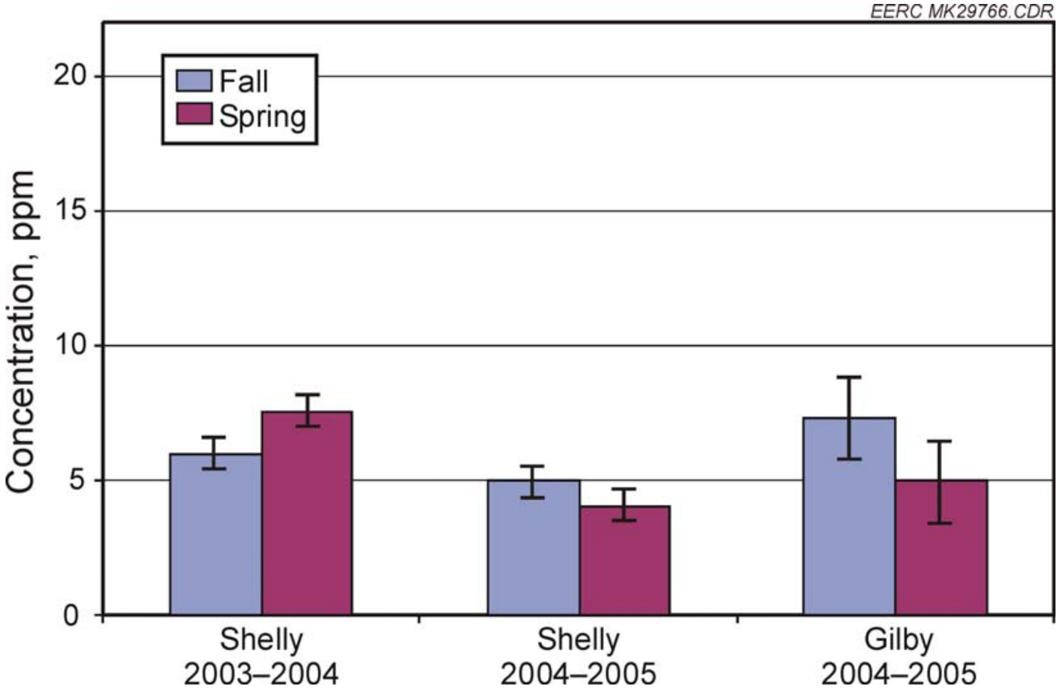


Figure 66. Fall and spring phosphorus content in nonflooded areas.

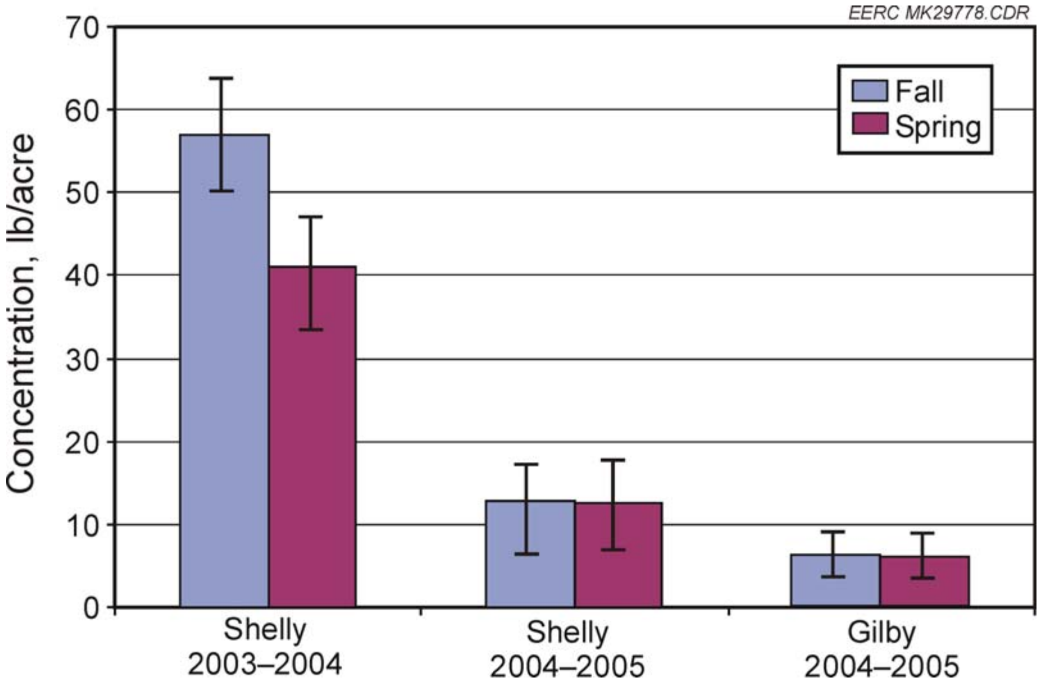


Figure 67. Fall and spring nitrate content in flooded areas.

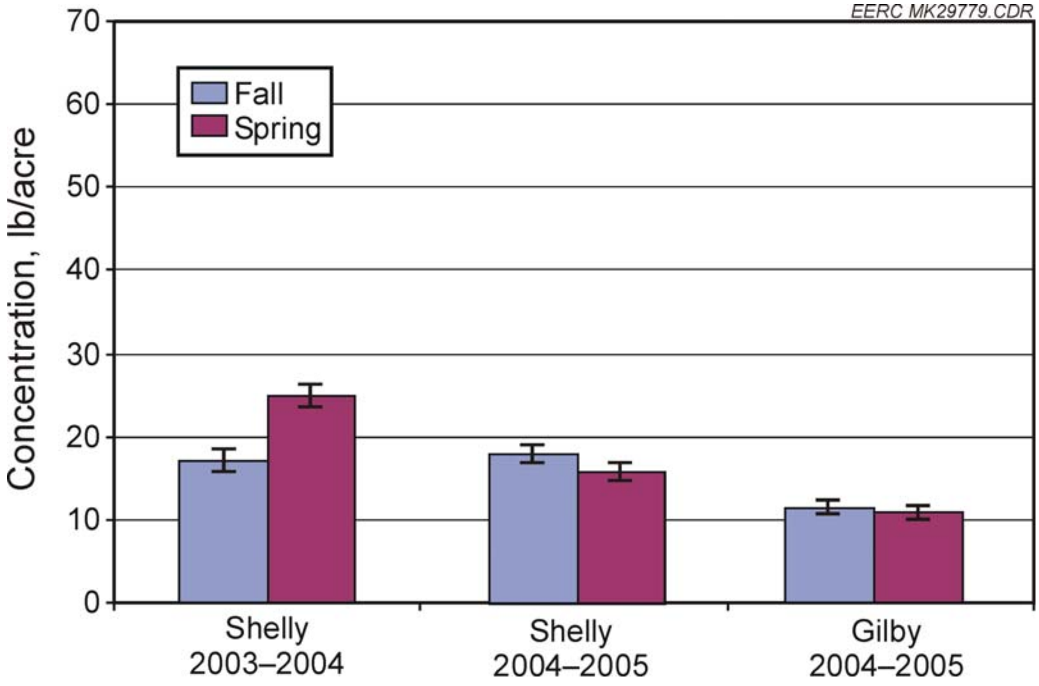


Figure 68. Fall and spring nitrate content in nonflooded areas.

decrease in nitrate from fall to spring, whereas the nonflooded portion of the site experienced an increase in nitrate from fall to spring. Nitrogen concentrations, as nitrite, nitrate, and/or nitrogen gas, often undergo considerable seasonal fluctuations for a variety of reasons, including soil moisture changes, fertilizer application, plant growth, and gaseous loss (Nortcliff and Wong, 1995). One of the key processes that convert nitrates to nitrites and eventually nitrogen gas is denitrification, which commonly occurs in low-oxygen (or anaerobic) environments. The decrease in nitrate in the flooded soils could be explained either by downward transport or denitrification, or both, which could be expected because the stagnant water storage limits the supply of oxygen to the subsurface; however, it is uncertain what caused the increase in the nonflooded soils.

Soil potassium concentrations are shown in Figures 69 and 70. Most of the changes that occurred from fall to spring were within the calculated standard deviation; however, the Shelly site in 2004 and the Gilby site in 2005 illustrated decreases outside the sample standard deviation on the nonflooded areas of the site. The Shelly site decreased from an average of 254 to 194 ppm, and the Gilby site decreased from 319 to 252 ppm, with standard deviations of 16 and 19, respectively. Since these changes occurred on nonflooded portions of the site, they cannot be attributed to factors associated with the stored water.

The sodium and chloride concentrations in the soils of the field trial sites are shown in Figures 71–74. Concentrations of these constituents in the soils of the Shelly site exhibited no change outside the calculated standard deviations. However, sodium and chloride concentrations at the Gilby site decreased from an average of 304 to 133 ppm and 9501 to 252 ppm, respectively, which is consistent with a trend of decreasing water-soluble constituents over time at this site. This trend was likely a result of dissolution of these constituents from the soils into the overlying water stored at the site. This is supported by a concomitant increase in these constituents in the water quality samples collected from the site. Unfortunately, a mass balance between the constituents dissolved from the soils and those that increased in the water samples at this site is infeasible because of the large standard deviation of these constituents in the site soils.

The soluble salt concentrations at the Shelly site exhibited very little change between the fall and spring analyses, as shown in Figures 75 and 76. The Gilby site, however, illustrates a decrease in soluble salt concentrations from 2.67 to 0.97 mS/cm on the flooded portion of the site, with a standard deviation of 0.80 ppm. Although this reduction is not quite outside the standard deviation of the samples, it mirrors the trend of decreasing soluble constituents, such as sodium, chloride, potassium, and calcium, within the flooded soils of this site as the length of storage increased.

One of the concerns over water storage from local agricultural representatives was that important nutrients such as phosphorus, nitrogen, and potassium would be leached from agricultural land by water standing on the soil in the spring. This may be a legitimate concern in some areas within the RRB; however, there were no consistent changes in soil chemistry in the sites evaluated as part of the Waffle field trials. For example, although there was a slight reduction in nitrate concentrations in the flooded soils of the Shelly site during 2004, there was no change in nitrate concentrations during 2005. Phosphorus concentrations decreased significantly from fall to spring in flooded soils of the Gilby site; however, no decreases in

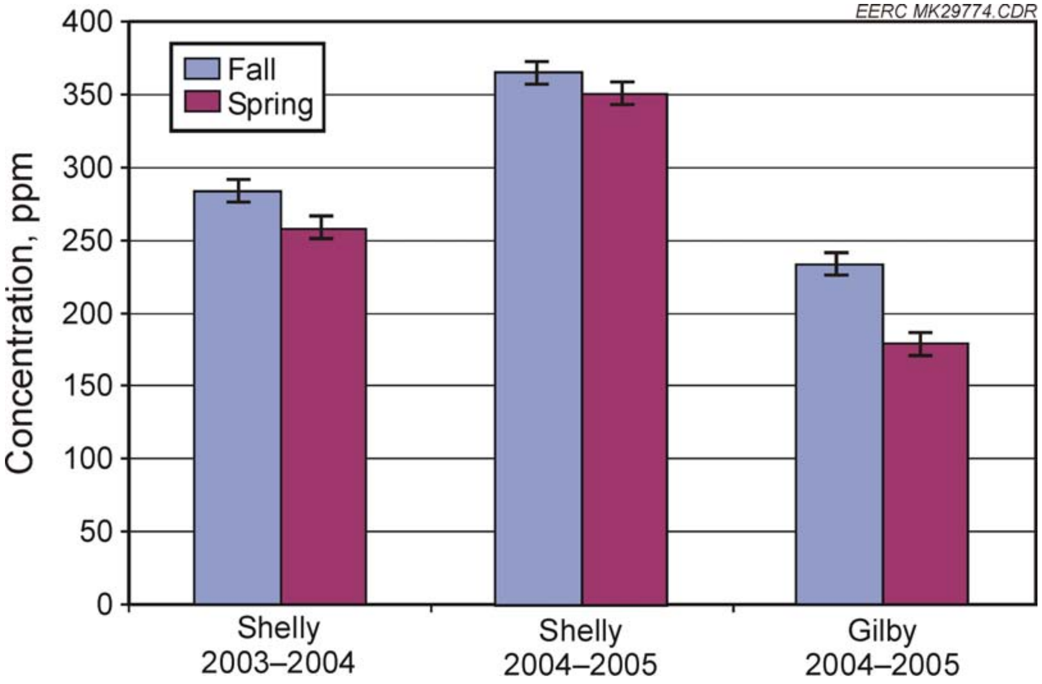


Figure 69. Fall and spring potassium content in flooded areas.

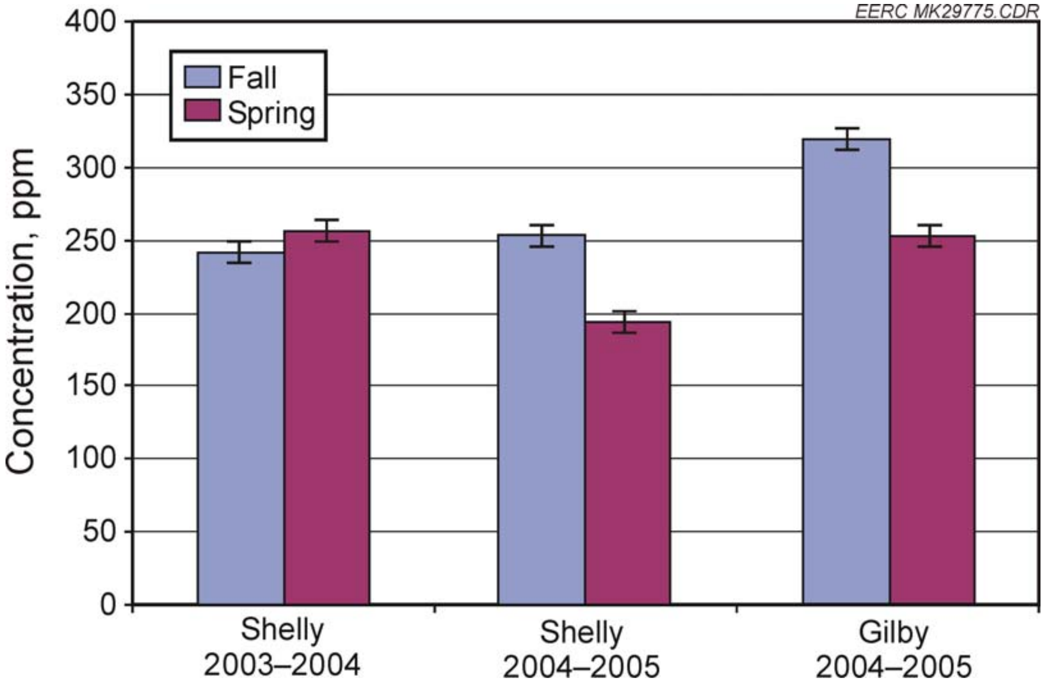


Figure 70. Fall and spring potassium content in nonflooded areas.

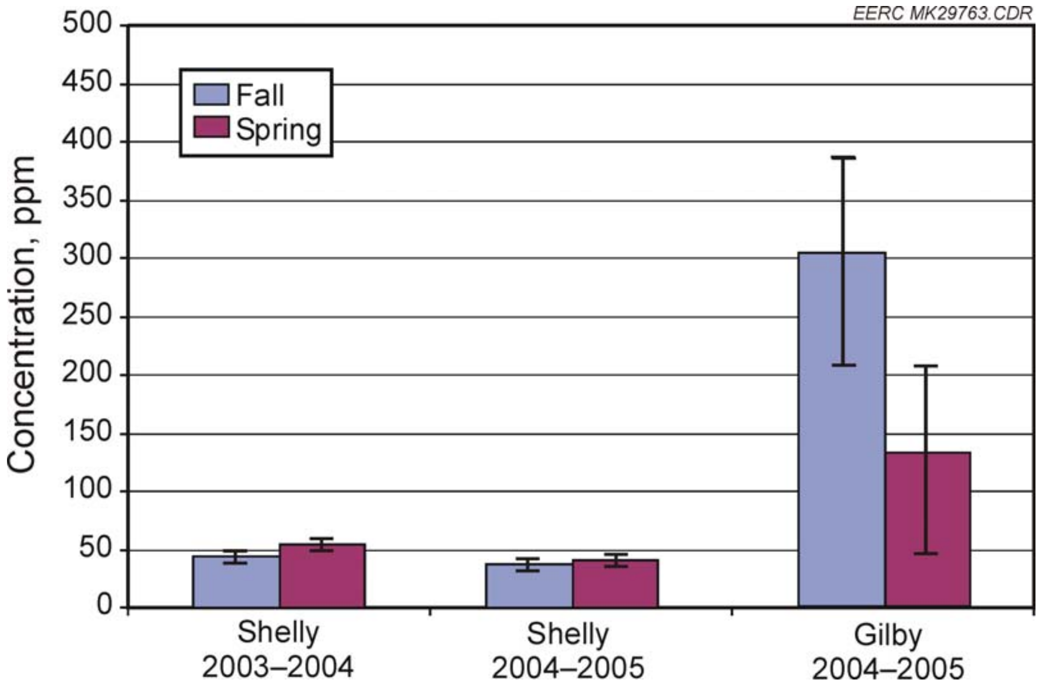


Figure 71. Fall and spring sodium content in flooded areas.

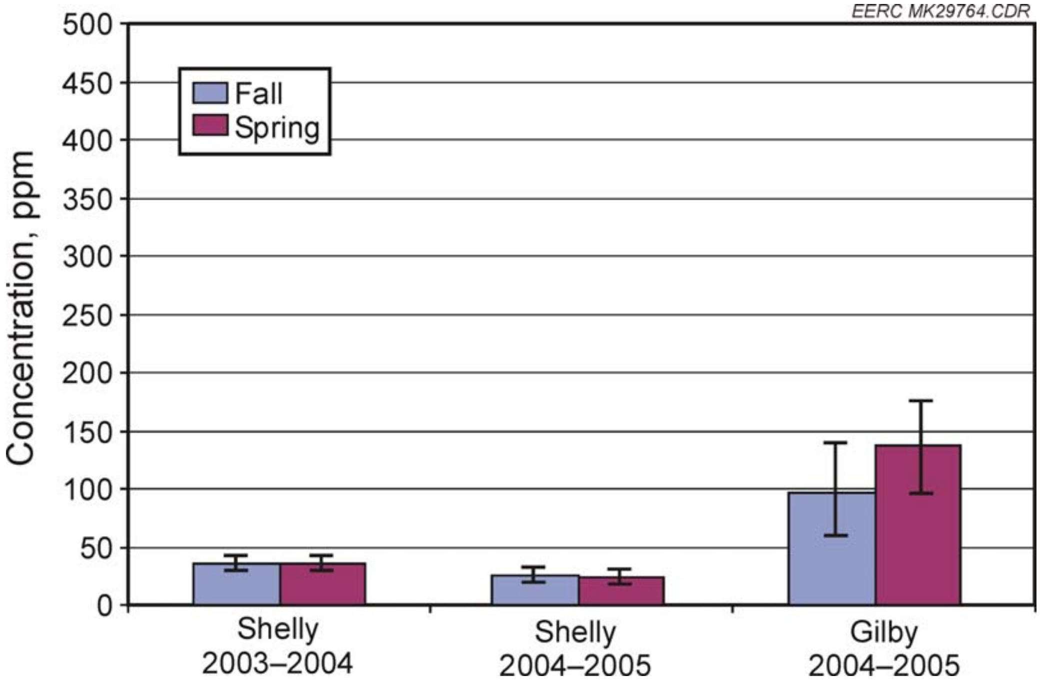


Figure 72. Fall and spring sodium content in nonflooded areas.

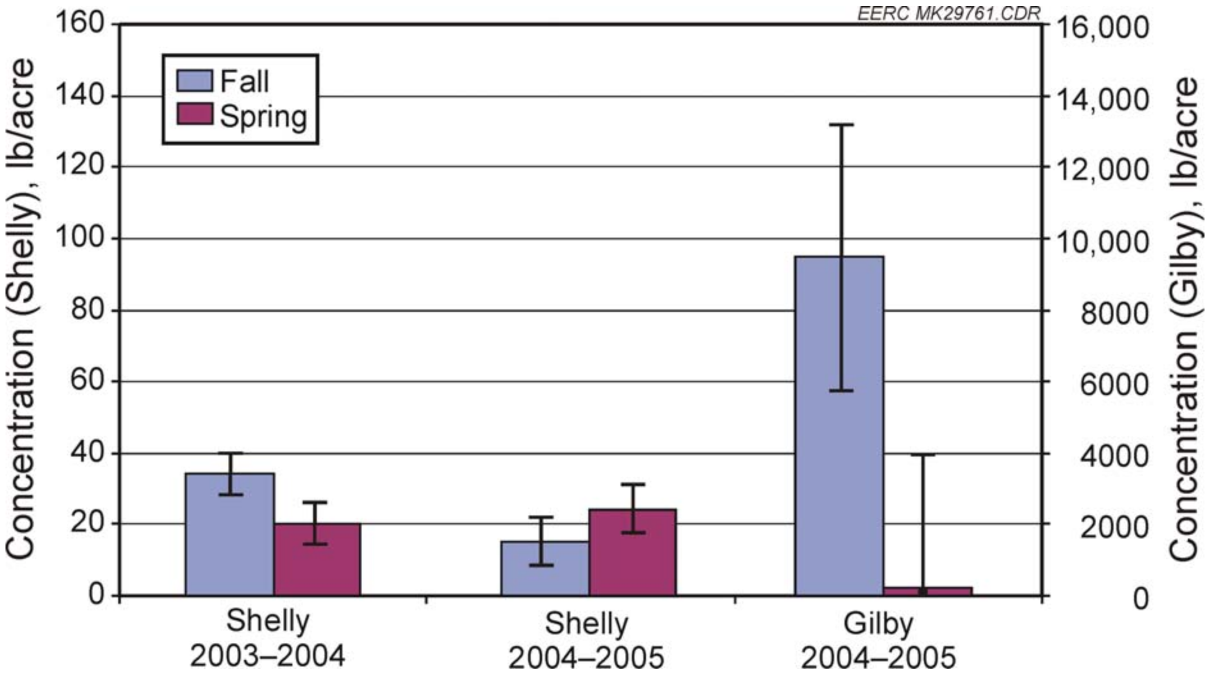


Figure 73. Fall and spring chloride content in flooded areas.

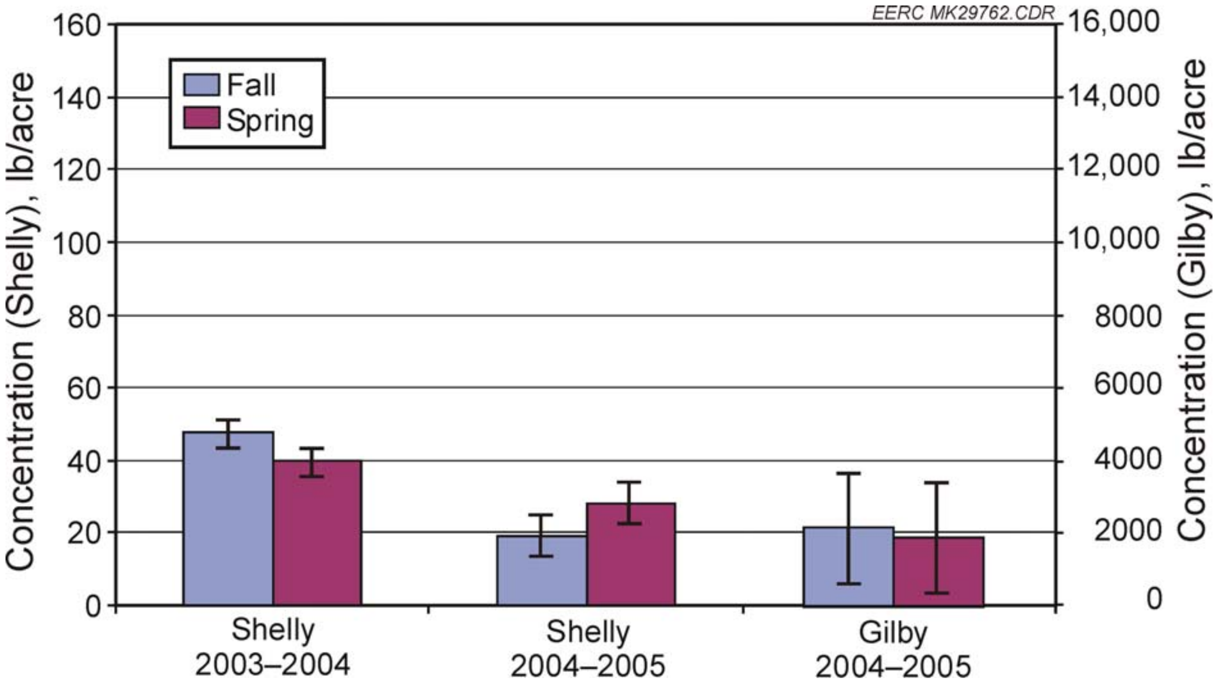


Figure 74. Fall and spring chloride content in nonflooded areas.

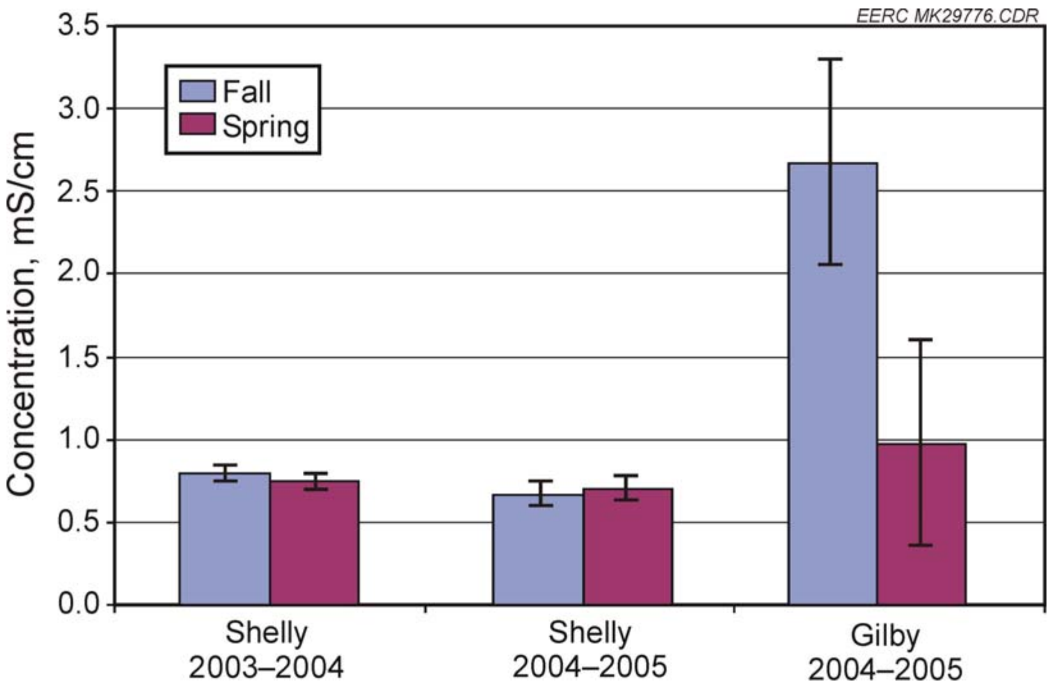


Figure 75. Fall and spring soluble salt content in flooded areas.

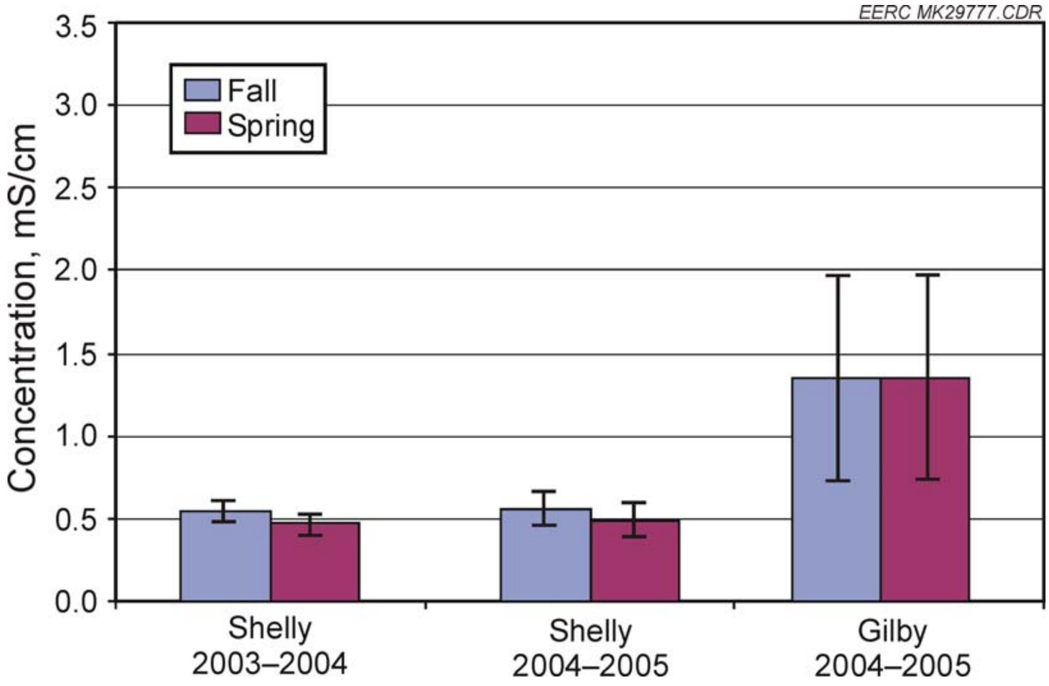


Figure 76. Fall and spring soluble salt content in nonflooded areas.

phosphorus were seen from fall to spring at the Shelly site. Therefore, it is possible that soil nutrients may be impacted by water storage; however, additional evaluations would have to be conducted in a wider range of soil types and in multiple locations throughout the RRB. Ultimately, if soil nutrient reductions were significant, this may need to be factored into the reimbursements provided to landowners who participate in the Waffle.

The one consistent trend exhibited by the soil quality data was a decrease in soluble salts, such as sodium, potassium, calcium, and chloride, in the soils of the Gilby site. The term soluble salt refers to the inorganic constituents (ions) that are dissolved in the soil water (University of Minnesota Extension, 2004). The concentration of soluble salts is quantified through measuring the conductivity of the soil water. Soluble salt levels are important because high amounts can reduce water uptake by plants causing restricted root growth, inhibited flowering, burned foliage, and limit yields (University of Minnesota Extension, 2004). In the past, the high salt concentrations at this site were problematic and resulted in impaired crop growth (John Scott, personal communication, 2005). Therefore, the reduction in soil salt concentrations as a result of water storage could provide a benefit to this site and the many other salt-impacted areas throughout the region.

2.5.3.6 Crop Yield Evaluation

The Shelly site was the only field trial demonstration site location that was actively farmed. To understand the impact of extended water storage on agricultural land, evaluations of crop yield and health were performed by visual inspection and by in-field crop yield estimates. The crop evaluations were performed after both the 2004 and 2005 spring demonstrations.

During the 2004 growing season, sunflowers and corn were planted on the field trial site. A visual inspection in early fall revealed no difference in crop height or robustness between the flooded and nonflooded areas of the site. However, it was an unusually wet spring, and planting dates for the crops were about 5 days later than neighboring fields. This delay was expected to have minimal impacts on yields and associated farming operations. Yields were estimated for the corn and sunflowers in October of 2004, according to a method developed by the NDSU Extension Service (North Dakota State University Extension Service, 1999). The method involved selecting three separate rows of corn 10 feet in length and then counting the number of cobs on each plant and the number of kernels on each cob. The numbers of cobs and kernels and the spacing of the rows were then utilized in an equation to estimate total corn yield as bushels per acre. This process was conducted in several places throughout the field in the areas of interest (i.e., low area or high area) to obtain an average yield for each area. Corn yield was estimated at an average of 139 bushels per acre on the flooded portion of the field trial site and 136 bushels on an adjacent field that had not been flooded. This suggests that the minimal delay in planting resulting from water storage did not adversely affect yield. Sunflower yield was calculated using an NDSU Extension Service method similar to the one used to estimate corn yield. The sunflower yield estimates were identical in both the flooded and nonflooded areas of the field at approximately 1190 lb per acre, providing further evidence that the stored water had no significant impact on crop production. There were no comparisons with neighboring fields because other sunflowers were not planted nearby.

In 2005, sunflowers were the main crop at the field trial section, and yield estimates were again performed for both flooded and nonflooded areas. The yield estimate results for the flooded and nonflooded areas were 1134 and 1155 lb per acre, respectively. This 21-lb difference is well within a 5% margin of error and suggests a minimal difference between the flooded and nonflooded areas exists.

2.5.3.7 CRP Vegetation Evaluation

In 2005, three of the four field trial demonstrations occurred on CRP acreage. Potential effects to the CRP grasses from the extended storage of water in the spring were evaluated through visual inspection both on the ground and using infrared aerial images obtained for each site and adjacent fields on three different occasions throughout the growing season. The images were acquired by the Upper Midwest Aerospace Consortium (UMAC) using a color infrared camera mounted through the floor of a small single-engine airplane. Visual inspection of the CRP vegetation throughout the spring, summer, and fall did not reveal any obvious differences in vegetative health between the flooded and nonflooded portions of the sites. Also, no obvious differences were detected between the field trial sites and neighboring fields of similar cover. The infrared images were processed to enhance differences in vegetative health and, again, no discernible difference in vegetation between flooded and nonflooded areas was detected.

2.5.3.8 Road Stability Evaluation

The road stability evaluation was conducted during both the 2005 and 2006 field trials at the Lake Bronson site and was performed on a north–south oriented road. The water storage period during the 2005 evaluation was shorter than planned (5 days) because of a mechanical failure resulting in an unplanned early release. A second evaluation was subsequently conducted in 2006 for the full 14 days of planned water storage. The road stability evaluation primarily addressed concerns of potential issues such as washouts, surface instability, slope instability, and erosion from wave action. These concerns originated from observations in other situations where water was against a road for extended periods, but roadbeds were not frozen. It was unknown, however, how the temporary storage of water would affect the roadbed during early spring when roadbeds are fully and/or partially frozen.

2005 Evaluation: Although the 2005 road stability evaluation was conducted over a short storage period, the results still have utility. The data collected from the sensors indicated that the road was still frozen and stable enough to prevent damage from the adjacent standing water and vehicle travel throughout the 5-day demonstration period. The frost layer present in the road apparently inhibits downward migration of the surface melt water, therefore, providing a stable frozen subbase within the road. The presence of the frost layer actually reduces the depth of the critical failure plane, thereby eliminating the potential for total road failure. As shown in Figures 77 and 78, the frost layer was continuous across the road, through the shoulders of the road, and throughout the ditch slope in both the flooded and nonflooded areas at the time of release. Also, there did not appear to be any visible erosion on the side of the road exposed to the standing water and wave action throughout the 5-day storage event. The frost depth was of similar thickness between the flooded and nonflooded locations, indicating that the presence of water did not appear to impact the rate of frost removal.

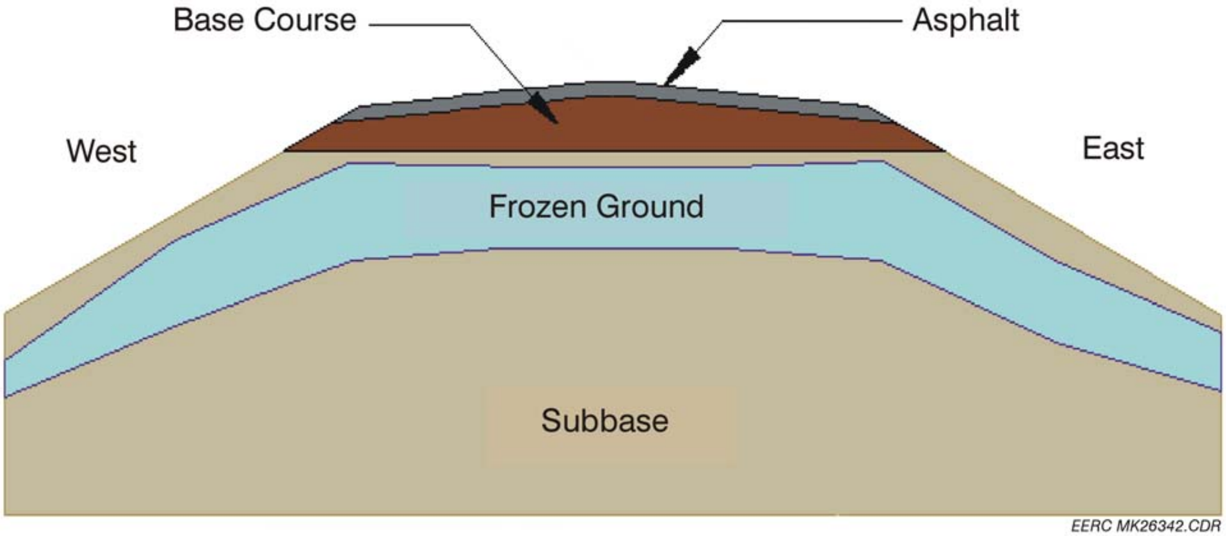


Figure 77. Frost profile for the nonflooded area of the road at the time of release on April 3, 2005 (Lake Bronson site).

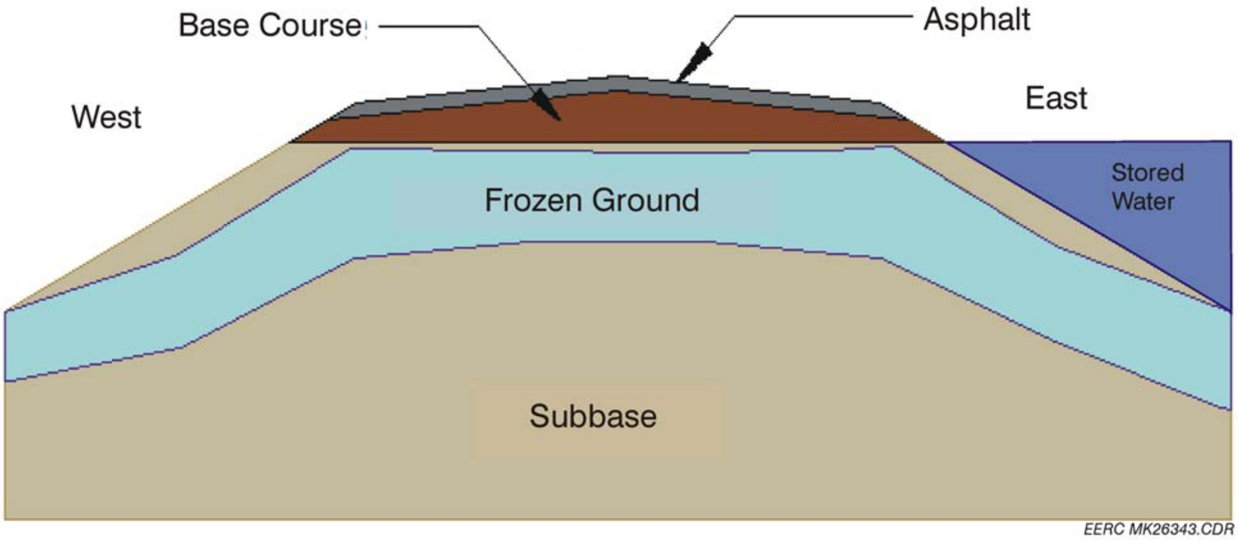


Figure 78. Frost profile for the flooded area of the road at the time of release on April 3, 2005 (Lake Bronson site).

2006 Evaluation: In 2006, the water was stored for the entire 14-day period. Although more of the frost had melted from the road subbase, it still appeared sufficient to prevent road damage from the standing water. In the area where water was stored against the road, there was more frost present in the roadbed, shoulder, and ditch slope than in the area not subjected to standing water. Figures 79 and 80 illustrate the frost location within the road at both the nonflooded and flooded areas during the 2006 demonstration, respectively.

As can be seen in Figure 79, the frost layer dips in the center of the road. This occurs as sunlight is adsorbed by the pavement, causing the frost directly under the pavement to melt. This saturates the road, and because the ground remains frozen beneath the saturated lens and the shoulders of the road, the water remains trapped in the center of the road. This water-saturated sediment is subjected to high pore pressure when vehicle travel over the road occurs, and if the pore pressure is high enough, it can cause the pavement to fracture or heave. To minimize damage from this condition, road restrictions are put in place by DOT, limiting the weight of vehicles traveling on certain roads during this time of year. However, standard cars and light trucks do not usually cause harm to the road during this time, and only heavy vehicles and trailers are restricted. Once the frost is entirely thawed, the excess moisture in the subbase is able to drain and road restrictions are removed.

2.5.4 Conclusions

The field trial demonstrations addressed a variety of issues related to the potential implementation of the Waffle concept. The first objective was to provide a proof-of-concept demonstration to show that extended water storage could help alleviate potential flooding by reducing peak flows in waterways adjacent to the site, which would lead to flow reductions in downstream tributaries and in the Red River itself. The evaluation successfully demonstrated that local flows (adjacent ditches and waterways) could be reduced by 20%–30% and that the timing of release would generally occur well after the peak flows on the tributaries and the Red River. The field trials also demonstrated that a minimum period of water retention (7–14 days) was sufficient to provide these flow reductions.

Another key goal of the field trials was to evaluate the effects of water storage on the landscape and on the environment. A summary of the significant results of the Waffle field trial demonstrations is as follows:

- No significant changes in water quality resulted from the extended water storage, except at the Gilby site, where the soils had high naturally occurring salt concentrations. Despite the increase in soluble salt concentrations in the stored water, the levels were still less than those measured in nearby ditches unaffected by the field trial.

- Although some flooded soils exhibited decreases in nitrate and phosphorus concentration, the soil chemistry results were not consistent from site to site or from year to year. Additional testing would have to be conducted to establish a relationship between water storage and nutrient concentration changes, if one exists. The soil chemistry results did exhibit consistent trends in soluble salts at the Gilby site, concentrations of which decreased over time. The flushing of salts from agricultural

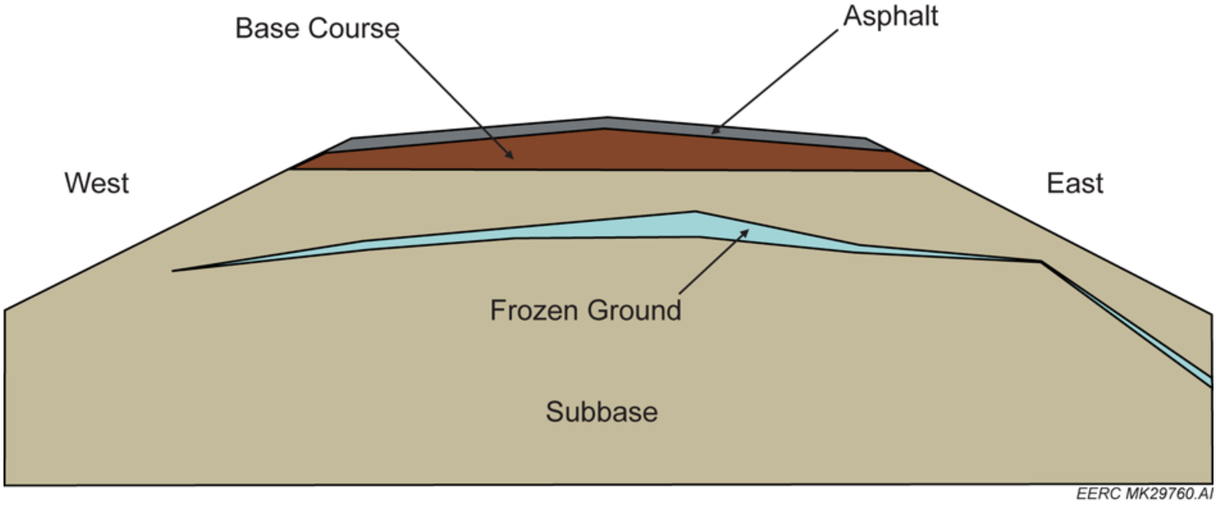


Figure 79. Frost profile for the nonflooded area of the road at the time of release on April 13, 2006 (Lake Bronson site).

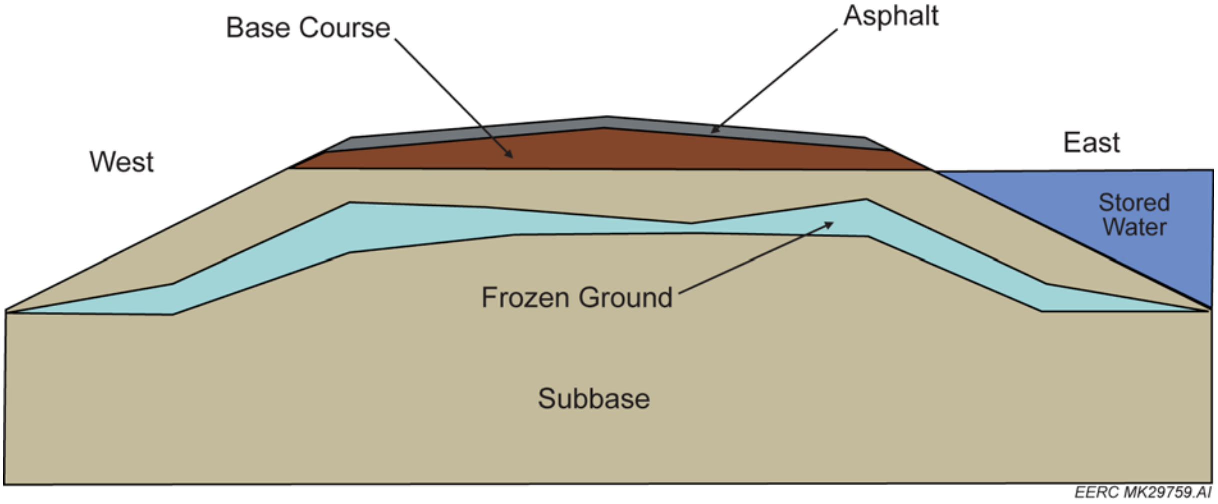


Figure 80. Frost profile for the flooded area of the road at the time of release on April 13, 2006 (Lake Bronson site).

land could provide a benefit if salt concentrations are high enough to inhibit crop growth.

- Crop yield estimates indicated that there were no adverse impacts to the production of sunflowers or corn with the observed minimal delay in planting and the extended water storage period.

- Water losses in the storage parcels due to infiltration and evaporation were significant, indicating that Waffle storage could help reduce the overall volume of floods. The infiltration of water to the subsurface could also play a key role in helping to increase soil moisture and recharge groundwater supplies during periods of drought. This is supported by the fact that soil moisture was maintained at higher levels for a longer duration on the flooded portions of the field trial parcels.

- Soil temperature evaluations indicated an accelerated rate of frost removal from soils underlying water storage areas.

- There does not seem to be any significant negative agricultural or environmental effects from the short-term storage of water on agricultural or CRP lands using the Waffle water storage concept.

- Evaluation of road stability indicated that sufficiently thick frost lenses are present within the roadbed during water storage to limit infiltration and preserve road stability.

2.5.5 Recommendations

After conducting the Waffle field trials, the EERC recommends the following for future implementation of storage sites:

- There are several efforts under way to collect high-resolution digital elevation data for the RRB using Lidar. This would be extremely useful for quickly and efficiently evaluating the storage volume of potential Waffle storage sections and mitigating the need for time-consuming GPS surveys of each site. In addition, it would allow for delineation of the flooded and nonflooded portions of Waffle storage sites, which would help establish landowner reimbursement rates, especially on sections with multiple landowners.

- CRP is a federal program that could be used to facilitate the implementation, at least in part, of the Waffle flood mitigation concept. The program guidelines now allow water storage as an acceptable use of CRP acreage. In addition, FSA, which administers CRP, has expressed strong interest in using CRP acreage for temporary water storage as a means of mitigating flooding within the state. One alternative would be to provide an additional payment under the CRP contract for landowners to store water during certain years with an additional payment during those years. Another alternative would be to have a selection criteria for CRP contracts (since they are becoming more competitive) that gives preference to landowners willing to allow water storage when needed.

- Specific culvert modification designs should be developed and approved by individual county and state entities as acreage is enrolled in the program. Appropriate designs will be dependent on the location and type of drainage system being altered.

- Additional road stability testing should be completed that includes all types of roads, varying from extensively built asphalt roads to smaller county and township roads constructed of gravel and dirt. In addition, roads located in the southern portions of the RRB should be tested.

- Since the field trials demonstrated a considerable reduction in localized flows and runoff volume, large insurance companies and FEMA may have an interest in supporting a flood mitigation concept such as the Waffle. Reductions in insurance and disaster payments due to rural and urban flooding may justify the expense of a preemptive countermeasure to mitigate potential flooding.
- Before implementing Waffle storage in an area unfamiliar with the concept, it is advisable to hold public meetings or forums to further explain the concept and to address any landowner concerns. Since it is a relatively new concept, there tend to be questions regarding the length of storage, potential impacts to drainage, and the manner in which the water is released.

3.0 SOCIAL CONSIDERATIONS

3.1 Introduction

For thousands of years before widespread human settlement, the wetland-abundant landscape of the northern glaciated Great Plains remained largely unchanged. It was not until the Homestead Act was passed by Congress in 1862 that settlement and farming began to expand in the region (River Keepers, 2005). This act allowed settlers to claim 160-acre plots of land for a nominal fee after a minimum 5 years of settlement; however, with this commitment came many challenges. Floods, droughts, swamps, and swarms of mosquitoes were just a few of the hurdles faced by early settlers. One of the biggest obstacles was engineering the soggy landscape so that it was dry enough to farm and, as a result, ditches were constructed, many wetlands and wet areas were drained, and streams and watercourses were channelized. Over time, the region’s drainage system has become one of its most prevalent and widespread features, with an estimated 28,000 miles of legal drains located in the Red River Valley of North Dakota and Minnesota (Bluemle, 1997).

Agriculture continues to be the primary industry in the region, and it is the backbone of the economy. Currently, about 74% of the land area in the RRB is used for farming, 12% is forest, 4% comprises wetlands and water, urban land use accounts for 3%, and the remaining 7% falls into other categories (U.S. Geological Survey, 2006). Despite the prevalence of agriculture in the region, farming is a challenge, in large part, because of the unpredictable climate of the RRB. The RRB is located between the semiarid climate of central and western North Dakota and the wetter climate of Minnesota (Minnesota Department of Natural Resources, 2007). As such, sometimes the RRB experiences the drier conditions of the West, while at other times, it is influenced by the wetter conditions of the East. Coupled with more extreme regional wet and dry cycles, the range in climatic conditions can be quite dramatic.

Thus, at the beginning of this study, EERC researchers anticipated that the concept of temporary water storage on agricultural land may be viewed with skepticism by some farmers and/or landowners. Because farmers face many challenges due to the unpredictable climate of the RRB and uncertainty in agricultural commodity markets, they are understandably risk averse. Because temporary water storage could cause a delay in planting, it adds additional risk to farming. In addition, water storage counters convention in the RRB, because drainage has been the paradigm since settlement.

To better understand the key issues and concerns related to flooding, drainage, and the use of agricultural land for temporary water storage, the EERC conducted an extensive outreach effort to collect input from stakeholders across the region and to communicate the Waffle concept, project outcomes, and potential implications to stakeholders. After receiving input from both the AAB and the CAB, the key groups targeted for outreach included the following:

- Minnesota watershed districts and North Dakota county water resource boards
- North Dakota and Minnesota county FSA offices
- Minnesota county soil and water conservation districts
- North Dakota county soil conservation districts
- North Dakota and Minnesota township officer associations
- Service-oriented organizations, such as the Lion’s Club and Kiwanis Club
- Farming-related organizations, such as the Farm Bureau, Wheat Growers, and Grain Dealers Association

The EERC met with and/or gave presentations to the above groups, as well as a variety of other groups and organizations not listed above. In addition, numerous radio and television interviews were conducted, and numerous presentations were given at local, national, and international conferences. A complete list of all of the outreach activities conducted by the EERC to communicate the Waffle concept and to gather input is given in Appendix E.

In addition to meeting one on one with all the entities listed in Appendix E, more input from individual citizens and landowners regarding flooding and drainage issues, as well as what they believed were reasonable solutions to address flooding issues, was collected through two landowner surveys. Initially, a smaller survey was conducted as a pilot to gauge whether the questions were appropriately worded to generate the information we were seeking. Minor modifications were made to the first survey, and the revised version was sent to farmers and landowners throughout the entire RRB. The results of these surveys are discussed later in this section of the report.

Additional efforts to communicate the Waffle concept and to gather input included the development of a Waffle Web page and quarterly newsletters. The newsletters contained information about the project activities as well as key results and conclusions. The Waffle Project Web site was launched in February 2004. The site includes:

- General information about the Waffle project and activities, including key publications and reports.

- Copies of Waffle project newsletters.

- Images of flooding, the field trial, water storage, etc.

- General water management-related information including links to other Web sites and a brief description of those sites. Also included are general RRB maps and GIS-developed "theme" maps of the RRB, such as soil types, LULC, slopes, land productivity, etc.

- A list of AAB and CAB members, as well as the minutes from the Advisory Board meetings.

3.2 Summary of Landowner/Stakeholder Concerns

In an effort to evaluate the social feasibility of the Waffle concept, EERC staff adopted several approaches to gauge the concerns that landowners, farmers, and/or stakeholders have with respect to the Waffle concept and temporary storage of water on agricultural land. One approach, as previously mentioned, was to gather input from farmers and stakeholders across the RRB regarding key issues and concerns. Another approach involved consulting with the Waffle's CAB and AAB to identify and prioritize key social issues and concerns that could constrain Waffle implementation.

The key concerns and/or issues that pertain to the Waffle concept and/or Waffle implementation were grouped into seven broad categories:

- General questions about the Waffle concept

- Farmer and/or landowner concerns related to the impact of temporary water storage on their land and farming operations

- Concerns over how Waffle storage would affect and/or exacerbate drainage issues/problems between neighbors

- The impact of Waffle storage on roads

- The economic feasibility of the Waffle concept

- Operation and administration of the Waffle concept

- Funding for Waffle implementation

The ranking of key issues and concerns by the CAB resulted in the following list of specific issues considered particularly important: the education of landowners, drainage issues between landowners and neighbors, how to address summer floods, the possibility of land reclassification to permanent storage or wetlands, the economic feasibility of the Waffle concept and its implementation, duration of water storage on fields, crop insurance issues related to handling late planting dates, and whether there would be sufficient voluntary participation by landowners. All of these issues are addressed in the following summary of stakeholder issues.

The following section describes the key issues and concerns based on input gathered through the Waffle project outreach efforts. For simplification and ease in identifying key landowner concerns, the information is presented in terms of the most frequently asked questions (FAQs) encountered by the Waffle team. Many of the concerns were addressed fully or in part through the evaluation of the Waffle concept. Some of the concerns were beyond the scope of study of the project and, therefore, are mentioned but not addressed in great detail. Some of the questions pertaining to the Waffle concept itself are not included here since they have already been explained in prior sections of this report.

3.2.1 General Questions and Answers Regarding the Waffle Concept

The Waffle concept is already in place (i.e., road confinement) in the RRB and it doesn't work – it still floods. How is this different?

It is true that there is a significant network of roads and various other features that slow down water movement to the Red River and its tributaries; however, it is important to remember that this water is still flowing and, in many areas, the retention lasts for less than a week. The Waffle concept proposes to retain overland runoff for a longer period of time over a wider portion of the region and to control the release of water to the drainage system of the RRB. Currently, there is no strategy in place for managing a timed release of this water to prevent downstream flooding. If the flow of water can be released in a regimented manner to allow for gradual input to the river, it would result in less flooding and overland flow in the downstream areas.

In addition, areas that retain water with the current system tend to be located in the floor or bottom of the RRB, often referred to as the Red River Valley. The Waffle concept proposes to begin retaining water in the upstream regions of the RRB to control runoff where precipitation falls before it becomes a problem. The results of the Waffle modeling have shown that water storage in these areas has greater effects on flood reduction than storage areas located near the mouths of tributaries.

The Waffle is designed to mitigate major springtime flooding; what will the effects be on summer floods?

In recent years, major summer floods have caused severe damage to towns, farmsteads, and agricultural land. Unfortunately, the Waffle concept was not explicitly evaluated as a means of mitigating summer floods. It was the EERC's belief that using agricultural land already planted with crops as a means of flood mitigation would not be economically or socially feasible. The gated control structures used to retain springtime runoff for Waffle storage would be fully open during the growing season to allow for water drainage.

Although the Waffle concept was not designed to mitigate summer floods, the models developed and data compiled through the study will provide the water management professionals of the basin with a much-improved understanding of the drainage of the RRB and subbasins. The water management tools provided by this project could be used to develop emergency action plans for extreme weather events in each subbasin.

What about dry years? How would the Waffle plan affect the region during droughts?

The RRB is characterized by an ever-changing weather pattern for both short-term and long-term cycles. The past 15 years have been characterized by wetter-than-normal conditions; however, it is certain that in the future there will be dry periods such as those experienced in the 1920s and 1930s. When the farmers are battling the devastating effects of drought, more conventional flood control measures such as dikes will not be of any benefit. The infrastructure provided by the Waffle project will allow farmers to retain any available moisture on croplands in the spring and potentially allow for the increased recharge of precious groundwater resources. The databases and models provided by the Waffle project will allow water professionals to manage the resource more wisely.

Will the Waffle replace other flood control strategies?

Considerable effort and resources have been applied to other flood control measures in the RRB, including the building of dikes, dry dams, bypass structures, and wetland and riparian restorations. These strategies have been an effective part of our battle to mitigate flood damage and manage water in the basin. By reducing peak flows in the Red River and its tributaries, the Waffle concept provides an augment and enhancement to existing flood control measures.

In the past, the Waffle plan has occasionally been criticized by proponents of other flood mitigation strategies. We assert that any effective water management strategy needs to include a variety of options and a comprehensive basinwide approach. Too often, past flood control strategies focused solely on the major towns and cities, ignoring the devastating effects of flooding in the small towns, rural residences, and croplands of the basin. For example, the new dikes in Grand Forks–East Grand Forks are an effective deterrent to in-city flooding, but they do little to benefit the surrounding rural areas. The Waffle concept would provide relief for both rural land and municipalities.

The reality of water management in the basin is that we need to explore and pursue any feasible means of dealing with the natural climate cycles and extreme weather events that we experience in order to ensure the best possible future for our children and grandchildren. The information and models developed through the Waffle project will allow us to evaluate a variety of flood mitigation and water management strategies to develop comprehensive, basinwide plans for the future.

3.2.2 Questions and Answers Regarding Potential Impacts to Agriculture or Farming Operations

What about the impacts of the Waffle on agriculture?

Many of the potential storage areas available in the RRB are located on privately owned agricultural land. Since agriculture is the backbone of the region's economy, any practice that adversely affects agriculture is not in the best interest of our economy or our region.

One of the key components of this project was the investigation of the effects of water storage on agricultural land. Past studies have shown that temporary water storage prior to planting can have both positive and negative effects. For example, the enhanced soil moisture that may result from implementation of the project may be beneficial to crop yields during dry years. The "Create-A-Wetlands" study demonstrated this effect (BlueStem Incorporated, 1996; Spoor, 1992; Schroeder and Goldman, 1990). On the other hand, the short-term storage of water on agricultural land and the additional soil moisture could cause a delay in planting, which could adversely affect crop yields.

Historic records of major spring floods in the region show that the average date of peak flows is April 12 in Fargo and April 16 in Grand Forks (USGS National Water Information System). If water were released from Waffle storage sections approximately a week after peak flow dates during major spring floods, the release dates would occur sometime between April 19 and April 25. If it took approximately 2 to 3 days for the site to drain (as seen in the field trials) and another 2 to 3 weeks for the site to dry enough for planting, then the fields would be planted by May 5 to May 18. As shown in Table 25, this would likely accommodate the optimal and final planting dates listed for most crop types. However, it may not be soon enough to meet the contractually required and/or optimal planting date for sugar beets and potatoes (see next question).

For comparison, the water release dates of the field trials occurred between April 8 and 13 (except for the site near Agassiz Wildlife Refuge, which was not released until April 21 because of high water levels in the ditches adjacent to the storage site). These dates are earlier than those previously given as the likely dates of water release. During the 2004 Shelly field trial, there was an estimated 5-day delay in planting of sunflowers and corn compared to neighboring fields, corresponding to a corn-planting date of April 29, 2004. Crop yield estimates conducted at the end of the growing season showed no statistically significant differences in crop yield between flooded and nonflooded portions of the trial site, as well as between flooded portions of the trial site and adjacent fields. During the 2005 Shelly field trial, the crops (sunflowers) were not planted until early June; however, this was also the case with surrounding fields since the wet spring conditions prevented the majority of fields in the area from being planted earlier.

Soil moisture and temperature tests conducted at the field trial sites showed an accelerated rate of frost removal and increased soil moisture in the soils underlying areas of water storage. While an earlier removal of frost from the soils could facilitate an early planting date, the increased soil moisture could delay planting. Ultimately, the impacts of temporary springtime

Table 25. Average Optimal Planting Dates for the Region and Final Planting Dates to Qualify for Federal Crop Insurance

Crop Type	Average Optimal Planting Date[1]	Final Planting Date for Federal Crop Insurance[2]
Wheat/Barley	April 21 to May 15	May 31
Oats	No later than May 15	May 31
Corn	May 1 to May 10	May 25
Canola	May 15	May 10
Sunflowers	May 25	June 10
Soybeans	May 1 to May 15	June 10
Dry Edible Beans	May 12 to 31	June 10
Potatoes	May 1	June 10
Sugar Beets	April 20 to May 10	May 31

[1] North Dakota State University, 2006; Lykken, 2006.

[2] USDA Risk Management Agency: 2007 Commodity Fact Sheets; www.rma.usda.gov/aboutrma/fields/ mn_rso/.

water storage will likely vary considerably given the large range of weather conditions encountered in the RRB from spring to spring. To account for this uncertainty, the economic feasibility of the concept under a wide range of storage scenarios and landowner reimbursement amounts were evaluated by economists at NDSU. For additional details, see NDSU's report located in Appendix H and discussed in Section 4.0.

What effect could voluntary participation in the Waffle have on farmers who have crop production contracts with industry?

One of the leading contract crops in the region is sugar beets. "Total direct economic impacts from the sugar beet industry (sugar beet production, processing, and marketing) were estimated at $1.1 billion in 2003," for the Red River Valley, west central Minnesota, and northwestern North Dakota/northeastern Montana (Bangsund and Leistritz, 2004). Of these direct impacts, 94% can be attributed to the sugar beet industry of the RRB. Because the sugar beet industry has such a significant economic impact on this region and because sugar beets are typically one of the first crops to be planted in the spring, the Waffle project team approached the American Crystal Sugar Company (ACS) in September 2005 to determine how landowner participation in the Waffle concept could impact grower contracts with ACS. Discussions with Thomas Astrup, ACS Vice President of Agriculture, indicated that if the industry believes that temporary storage of water on the land could jeopardize the planting of sugar beets and/or the growing of sugar beets, then the industry would disallow this practice. However, with Waffle implementation, if favorable planting conditions facilitated a May 1 planting date, then there would be no objections to this water management practice on sugar beet acres.

A similar conversation was held with Duane Maatz, President of the Northern Plains Potato Growers Association. Mr. Maatz indicated that while individual contracts between industry and growers vary, typically growers would not be restricted from participating in a practice like the Waffle; however, growers are contractually obligated to produce a certain quality of potato. If the quality of the potatoes was impacted by water storage (i.e., because of a later planting date), the grower would experience a loss of revenue. The primary concern is with potatoes grown for processing of food products, since these should be planted by May 1.

Meeting the May 1 planting date for sugar beets and potatoes could be challenging. As mentioned previously, based on historical peak flood dates, the water would likely be released from Waffle storage sections sometime between April 19 and April 25. If it took approximately 2 to 3 days for storage sites to drain (as seen in the field trials) and another 2 to 3 weeks for the sites to dry enough for planting (assuming no prolonged rain events), then the fields could be planted between May 5 and May 18. Although planting dates close to May 5 may be early enough for sugar beets and potatoes, dates closer to May 18 would likely be too late. During the 2004 Shelly field trial, water was stored for a 14-day period at the site, lasting from March 26 to April 9. The estimated planting date of the site was April 29. This would have been early enough to meet the May 1 sugar beet deadline, but it would have been very close. During the 2005 Shelly field trial, the crops (sunflowers) were not planted until early June; however, this was also the case with surrounding fields since the wet spring conditions prevented the majority of fields in the area from being planted earlier.

As with other crop types, ultimately, the farmer/producer would have to decide whether the reimbursement received for Waffle participation was high enough to cover potential crop losses. In some instances, depending on the terms of contracts, participation in Waffle storage might not be possible. If the Waffle is implemented on a widespread scale and additional data become available on water release and planting dates, it will be easier to decide whether it is feasible to use sugar beet or potato acres for temporary springtime water storage.

How would crop insurance companies handle late planting dates caused by the Waffle?

Federal Crop Insurance Corporation (FCIC) programs are administered by the Risk Management Agency (RMA), which underwrites crop insurance policies for hundreds of crops and livestock in the United States (Risk Management Agency, 2007). As shown in Table 24 and discussed previously, the likelihood of a planting date exceeding the deadlines published by RMA due solely to water storage in Waffle sections is small; however, it is possible that frequent and/or prolonged rain events that occur after water release could extend the planting date beyond that needed to meet RMA guidelines. Because the Waffle is still a concept and not associated with any program, there are no policies in place that define landowner reimbursement terms and/or how the Waffle may or may not operate in conjunction with existing federal programs.

One example of how the Waffle may work in conjunction with crop insurance was exhibited in FY2000 legislative amendments to the FCIC crop insurance program that allowed for the development of federally subsidized crop insurance policies where the use of the policy can be shown to encourage sustainable agricultural practices. Revenue loss associated with crop damage or delayed planting from temporary water storage on agricultural lands to avert damage associated with downstream flooding can potentially qualify for compensation under the program. The legislation also allows for coverage of the costs associated with developing the insurance policies. Data and models from this report can possibly be used to develop the risk/compensation ratios necessary for development of insurance policies.

If I participate in the Waffle, how does this affect my land during the summer?

The Waffle concept is only being proposed for mitigation of large springtime events; therefore, the culvert modifications are designed so that water can be retained during the spring and not during the summer. The standpipe and control gate are fitted to the existing culvert; therefore, the culvert does not lose any drainage capacity during the summer months. If the land was utilized for water storage in the spring, the gated culvert would be left open to allow the section to drain during late spring and summer precipitation events.

That being said, it is not up to the EERC to decide when the Waffle concept should or should not be implemented. An area of future work may be to evaluate the economic feasibility of implementing the Waffle for major summer flood events.

Would farmers receive payments for storing water on agricultural lands?

Ultimately, this would have to be decided by the policy makers or stakeholders that implement the Waffle concept; however, in evaluating the concept, the EERC assumed that landowners would require reimbursement for participation. Thus, as part of the economic evaluation of the Waffle concept conducted by NDSU, various payment structures were evaluated based on the estimated rental values of the land. The general assumption is that landowners or farmers would receive a sign-up bonus for agreeing to participate, plus an additional payment in the event that water was stored on their land. Again, additional information on the economic evaluation can be found in Section 4.

Would there have to be differences in farming methods compared to "normal" years?

This is difficult to predict without having results from extensive, widespread implementation. As shown by the field trials, there could be delays in planting. Although this did not affect the crop type planted by the farmer during the trial or the crop yields, an extended delay would be more problematic and may affect the type of crop the farmer decides to plant.

Some crops would be more of an issue than others, such as sugar beets, which need to be planted as early as possible in the spring. One way to help alleviate this issue for those interested in participating would be to allow farmers with multiple sections of land to decide which parcel would be used for water storage. This would help minimize disruption in agricultural practices.

Ultimately, it is important to remember that the Waffle is proposed to help mitigate very large springtime floods like 1997 (unless landowners decided to store water to improve soil moisture during drought conditions). Floods the size of 1997 do not normally occur on an annual basis. Thus Waffle participants may only be asked to store water once or twice every 10, 20, or 50 years.

Would farmers who agreed to participate be notified in the fall, prior to chemical application on farmland, if the Waffle concept would need to be implemented?

Unfortunately, no. There is no way to predict the severity of springtime flood events prior to having data on winter snowfall accumulations. Because the Waffle is proposed for mitigation of severe springtime events, the likelihood of it being implemented during any given year is low. If it was implemented and farmers spent time and money applying chemicals in the fall, they should be reimbursed accordingly, or they would need to determine if the reimbursement rate they agreed to was sufficient to cover those costs.

Once a producer implements the Waffle, is there a chance that the land could be reclassified as a wetland by the U.S. Fish and Wildlife Service (USFWS)?

No. Waffle project team members had repeated conversations with representatives from the USFWS offices in Minnesota and North Dakota. These representatives confirmed that temporary storage of water on agricultural land during the spring does not qualify it as a wetland. In addition, USFWS cannot enter into a wetland easement without consent from the landowner.

That being said, in some areas of the RRB, particularly in North Dakota, there is mistrust of USFWS among some landowners as a result of past disagreement and misunderstanding over wetland easements (William Schuh, personal communication, 2006). This issue is widely debated between landowners/producers and various state and government agencies; however, it is not appropriate for the EERC to decide whether landowners are justified in their mistrust of USFWS. The fact of the matter is that as long as there is a perceived mistrust of USFWS, steps should be taken to assure future Waffle participants that portions of their land will not be designated as wetland as a result of Waffle storage. This may simply be a matter of including a clause to this effect in the landowner contract.

3.2.3 Questions and Answers Regarding Drainage Issues

If you hold back water in one area, won't that flood another landowner's field?

No. If the Waffle concept were implemented, a precise survey of each storage area would be conducted to determine the maximum elevation of water that could be allowed in each field without backing water up onto neighboring land. To control the elevation of water stored on a section, existing culverts would be fitted with overflow standpipes and gated culverts that would allow water to be stored on the parcel up to the designated elevation, after which it would spill into the top of the standpipe and continue to flow through the drainage system. For example, during the Waffle field trials, no land was flooded that was not owned by someone who agreed to participate in the trials.

When the water is released from Waffle storage areas, won't it flood land downstream?

The release of water from Waffle storage sections would be controlled to minimize downstream impacts. By modifying the existing culverts with canal gates or a variable-flow control gate, the water can be released slowly from a storage section. This also helps minimize erosion from the storage parcel and within the adjacent waterways. Once a storage area is completely drained, the culvert would be opened to maximum capacity to accommodate late spring and summer rain events.

3.2.4 Impacts of Waffle Storage on Roads

Would road integrity be jeopardized if the Waffle concept were implemented?

Because roads were not designed to retain water, this was a key question that was addressed through the Waffle study. At the beginning of the study, an extensive literature and Internet search was conducted on this topic; however, no published information was found. Additional searches through the Transportation Research Information Services (TRIS) of the federal government, DOT Federal Highway Administration (FHWA), and the National Cooperative Highway Research Program (NCHRP) also yielded no information or data on this topic. Telephone conversations with 12 county engineers and road superintendents throughout the RRB have, however, resulted in some interesting comments and perspectives:

- A common consensus was that roads are not designed to be dikes. Further, such use of roads would violate present stream-crossing codes. The implication was that the implementation of the Waffle would require changes in state regulations.
- While some made it clear that the use of raised roads to hold water back could saturate the road base and weaken it, others believed that the road base would be frozen during the period of water storage in Waffle sections; therefore, road stability would not be affected.
- Several individuals indicated that while roads are not designed to be dikes, for short periods, surface highways would not be overly stressed by this type of flood mitigation usage, particularly where the roadbase consisted of clay.

The key concerns were twofold. One was that water would saturate the road subbase, causing road failure and/or sections of the road to sheer off. The second concern was that if water was stored too high against the road, wave action could cause water to top the road and eventually wash it out.

These issues were addressed as part of the Waffle field trials, discussed in Section 2.5. The results indicated that there is sufficient frost present in the roads during the time of water storage to prevent or limit water infiltration into the road base. This would limit the road sheer failure, or the collapse of the road banks. In addition, during the field trials, the standpipes were installed at an elevation that allowed a minimum 1-foot freeboard between the stored water surface and the lowest point on the surrounding roads. During the water storage period, no problems were encountered with wind erosion or road stability.

Results from this study indicate that Waffle-type storage may actually help prevent road damage in downstream/downgradient areas by reducing the overall runoff of the spring melt (through evaporation and infiltration) and by helping to control overland runoff and the flow of water in drainage systems. Typically, road washouts are caused by uncontrolled flooding, which the Waffle concept aims to minimize. In addition, results of the storage volume analysis conducted in this study show that storage volumes could increase considerably in some areas if the low points on roads were built up. Discussions with township board supervisors have indicated that structural enhancement and raising of low areas in selected roads may be desirable since, in many areas, the deterioration of the roads is so severe during the spring thaw that it precludes travel over broad areas, resulting in problems for school transportation and response times for emergency vehicles. By coordinating flood control and road safety efforts, everyone will benefit.

Would current North Dakota stream-crossing codes have to be revised to implement the Waffle concept?

The Waffle concept primarily involves utilizing the existing road network to temporarily retain water during the spring. A key concern of stakeholders in the RRB was the potential legal ramifications of utilizing roads to store water since Chapter 24-03 of the North Dakota Century Code states that highways must be constructed "in accordance with the stream-crossing standards prepared by the department and the state engineer so as to avoid the waters flowing into and accumulating in the ditches to overflow adjacent and adjoining lands" (www.legis.nd.gov/cencode/t24c03.pdf). The Century Code also states that, "in the construction of highways the natural flow and drainage of surface waters to the extent required to meet the stream-crossing standards prepared by the department and the state engineer may not be obstructed, but the water must be permitted to follow the natural course according to the surface and terrain of the particular terrain." Because the Waffle is intentionally designed to impede the natural flow of water through temporary storage on agricultural lands, it likely conflicts with the North Dakota stream-crossing codes.

Minnesota regulations have similar provisions that govern the construction of roads and limit the impediment of natural flows by roadways. However, both North Dakota and Minnesota provide provisions to deviate from these standards. In North Dakota, a request to deviate from the standards can be made in writing by any individual and/or entity. A deviation from the standards can be approved by the state engineer and the director of the department of transportation if the reason for the deviation is deemed as a "good and sufficient cause" and as long as the crossing meets scientific highway and engineering standards.

The Minnesota road design manual indicates that MNDOT may change drainage patterns and facilities with the approval of several agencies, at a minimum, the Department of Natural Resources (DNR), for projects related to public or private water as specified in Minnesota Statutes Chapter 105; county commissioners and joint county ditch authority for issues related to drainage ditch systems as specified in Minnesota Statutes Chapter 106; and USACE for issues affecting the waters of the United States as specified by the Federal Water Pollution Act of 1972.

In the event of widespread Waffle implementation, it may be beneficial to amend the existing stream-crossing codes with a special provision that allows for retaining water in a Waffle-type manner as long as all affected landowners are in agreement and the stream-crossing capacities are not inhibited during summer months. Otherwise, site-specific requests to deviate from the standards would have to be made for each Waffle storage site.

3.2.5 Economic Feasibility of the Waffle Concept

Considering the number of storage areas that would be needed if the Waffle were implemented, would this approach be economically feasible?

This was also one of the key questions that the EERC faced at the beginning of the study. Initially, less emphasis was placed on the economic feasibility and more on the technical feasibility of the concept (i.e., how much it would reduce flooding). However, after recommendations from AAB and CAB, additional efforts were conducted to determine the economic feasibility of the approach. The economic evaluation of the concept was conducted by three economists at NDSU, Dean Bangsund, Dr. Eric DeVuyst, and Dr. Larry Leistritz. An overview of the economic analysis is presented in Section 4 of this report. The detailed results of the economic evaluation are contained within Appendix H of this report.

3.2.6 Implementation and Administration of the Waffle

If it is determined that the Waffle is feasible, who would implement the plan, and is participation mandatory?

Traditionally, large-scale water management has always taken a *command and control* approach. Too often, the traditional approach relied on heavy-handed legal tools like eminent domain and heavy equipment like bulldozers to accomplish water management goals. These tactics often subjugated the rights of individual landowners for the “greater good” as defined by the government, sometimes resulting in harm to the very communities and individuals the projects were designed to protect. Because the Waffle and other basinwide approaches rely on the cooperation of the entire region, such heavy-handed tactics will never be used to implement the project. The results of the Waffle project will be shared with local landowners, water resource boards, watershed districts, county commissions, and other local groups for their assessment and appraisal. They will be free to adopt the plan if they see sufficient benefit or reject it in favor of other strategies. We anticipate that the plan will be implemented for portions of the basin first, and other portions will adopt it when they see the benefits. In any case, we support *local control and basinwide cooperation and coordination* as the *only way* for the Waffle to be implemented.

Who would administer the Waffle plan if it’s implemented?

Again, the role of the EERC in this project was to evaluate the feasibility of the Waffle concept. How the program would be administered if implemented is beyond the scope of this study. However, insight gained by the EERC after meeting with so many different local and state organizations and agencies suggests that local agencies and/or organizations should play a key role in administering the plan. Local entities have more knowledge of the people and landscape than larger, more regional entities. In addition, the Waffle concept is most likely to be implemented for its local benefits prior to implementation for regional benefits; therefore, administration by local entities would be most appropriate.

3.3 Waffle Landowner Surveys

3.3.1 Introduction

One of the means of evaluating the social feasibility of the Waffle concept was to conduct a series of landowner surveys to explore public opinion regarding existing and potential flood management practices in the RRB. Since public opinion and support is an important part of implementing any flood mitigation strategies, landowners are an important element in the RRB system. The survey questions were attitudinal in nature. Some questions relied on respondents to predict their future interest or behavior. The survey employed open- and closed-ended questions to gather both qualitative and quantitative information. The open-ended questions also served as a public forum for landowners to offer their opinions and ask questions of EERC researchers.

Adoption of new practices depends on the willingness of producers to alter their current management and production practices. A change in one component of a practice will likely impact other components of the farming systems. This study begins at the attitudinal level with such measures as perceived risk of future flooding, consideration of participation in a future temporary storage program, and perceived usefulness of structural and nonstructural flood control measures.

The responses compiled in this study were collected from 1459 surveys returned from nearly 15,000 surveys mailed to a random sample of landowners and producers throughout the RRB. In developing the research, commonly asked landowner questions and concerns were integrated into the survey to address issues raised by landowners, including the socioeconomic aspects of a potential Waffle program. A copy of the final survey is included in Appendix F.

Agriculture is a way of life in the RRB, and long-standing agricultural practices and tradition are important to the basin’s residents. A new practice that may affect agriculture is essentially a social change that requires different behavior than prior generations and, therefore, challenges may be expected along the way. The participants in the basinwide survey were challenged to consider a relatively new concept, the Waffle, which deviates from tradition, but provides a potential solution to a long-standing problem—flooding in the RRB.

3.3.2 Methods

The first step in the research process was developing the landowner survey. Questions were derived based upon hundreds of meetings with landowners and stakeholder groups. Their FAQs and concerns were considered in determining the basis for the survey questions. During the fall of 2004, the first draft of the research instrument was tested with several landowners in Grand Forks (North Dakota) and Polk (Minnesota) Counties to ensure that the questions and answers were both understandable and relevant. This process was helpful for gaining insight into landowners’ level of understanding of the survey questions and to obtain their opinion on the survey length and design. Institutional Review Board (IRB) approval was obtained from the University of North Dakota (UND) prior to beginning the study.

The next step was to conduct a pilot study in the Wild Rice Watershed in Minnesota. The Wild Rice Watershed was selected as the location for the pilot study because the initial field trial demonstrations of the Waffle concept were also occurring in that area. In addition, the Wild Rice Watershed has been subject to several extreme spring and summer flooding events in the past decade and, therefore, landowners were likely to respond to a survey regarding flood issues. A full report of the Wild Rice results is found in Appendix G. Some of the relevant findings are also highlighted in this basinwide report. Overall, the results of the pilot study mirrored the results of the basinwide study, but the time frame differed by approximately 1 year. The Wild Rice region was again sampled in the basinwide study; therefore, that area is also represented in the basinwide results.

The pilot study included Becker, Clearwater, Mahnomen, and Norman Counties (all in Minnesota), and the response rate was 11.5%. Overall, the research process went smoothly and, hence, the key questions were retained for inclusion in the basinwide survey. A few changes were made in an effort to streamline the survey to keep the length reasonable for the respondents. For example, in the pilot study, respondents were asked to check the location of their land at the township level on a map, and they were asked to report on their average planting date of various crops. These questions had a very low response rate and were subsequently dropped from the basinwide survey.

As general project outreach continued and EERC team members met with additional landowners through forums like township officer and water board meetings, it became apparent that additional information was needed regarding landowner opinion on reimbursement costs. Hence, a section was added on the willingness of landowners to pay for a program like the Waffle. Experts in agricultural economics at NDSU provided the wording for the economic questions included on the survey. In addition, the survey results were utilized in the economic component of the feasibility study to help determine the range of acceptable payments by landowners.

Landowner names and mailing lists for the U.S. portion of the RRB were obtained from the Kansas City Administrative Office of the USDA FSA. From the initial list containing 53,000 records, duplicate names were removed. Next, 15,000 names were randomly selected and mailed a survey. Within the counties contained within the RRB, 64 townships were represented. Townships that did not contain land suitable for Waffle storage based on the criteria listed in Section 2.3.1 were eliminated from the opinion survey.

Since many addresses were undeliverable, the actual sample count was 14,750. Surveys were sent in a format similar to a newsletter, with a cover letter printed inside the front cover (see Appendix G). Survey participants were encouraged to respond with a small incentive of winning a digital camera, waffle iron, or gift certificates from area businesses. The response rate was approximately 10%, with 1459 surveys returned.

After the basinwide survey was completed, an additional survey was conducted to determine if the opinions of those that did respond were statistically different from those that did not respond. This "nonresponse survey" was conducted by randomly calling 281 nonrespondents and asking if they would be willing to fill out the survey if another one was mailed to them. Out of the 281 people contacted, 117 individuals completed the survey, for an overall response rate of 41.6%. There were very few statistically significant differences found between the basinwide study and the nonresponse study, indicating that the basinwide survey was valid. The only significant finding was a difference in the interest in participation and willingness to pay. These data are reported later in this report.

3.3.3 Perceived Risk

Humanity is at risk from a wide variety of natural disasters. Floods, earthquakes, landslides, tornadoes, tsunamis, and volcanoes can strike focused geographical areas. Others, such as droughts and hurricanes, can affect larger regions. Most of these natural disasters impact human populations regularly when viewed on the continental or global scale, although the odds of their happening in any one place in any one year are relatively low.

Americans have always feared floods, and with good reason (Haeuber and Michener, 1998). Floods are the most common and costly large natural disturbances affecting the United States. Approximately nine of every ten presidential disaster declarations are the result of floods. Floods took more than 200 lives between 1990 and 1995, and total flood damage costs between 1990 and 1997 reached nearly $34 billion (Haeuber and Michener, 1998).

In the survey, respondents were asked to select the level of risk that they believe exists for significant spring flooding to occur in the RRB in the next 50 years. An important consideration in understanding the landowners in the RRB is to gauge their opinion of their present environment and future risks. Figure 81 shows the respondents' perceived risk of spring flooding from high risk to no risk.

When asked about the level of risk that they believe exists for significant spring flooding to occur in the RRB in the next 50 years (examples of significant years of spring flooding include 1950, 1979, and 1997), the top two bars total 69.8%, which could be interpreted as the sample of landowners who feel at considerable risk of future flooding (see Figure 81). Although a large percentage of basin residents feel there is a significant future flood risk, translating these numbers into landowner willingness to take action is problematic. For four decades, social scientists have been studying how and why people respond to information and warnings about the risk of various natural disasters. Yet relatively little evidence exists on which to build a description of the basic social process that occurs between people's perception of risk and inclination to take action (Mileti et al., 1992).

3.3.4 Structural/Nonstructural Measures

The earliest approaches to floodplain management in the United States focused on structural measures to keep floodwaters away from existing or proposed developments. These measures included levees (dikes), floodwalls, channel improvements, and dam–reservoir

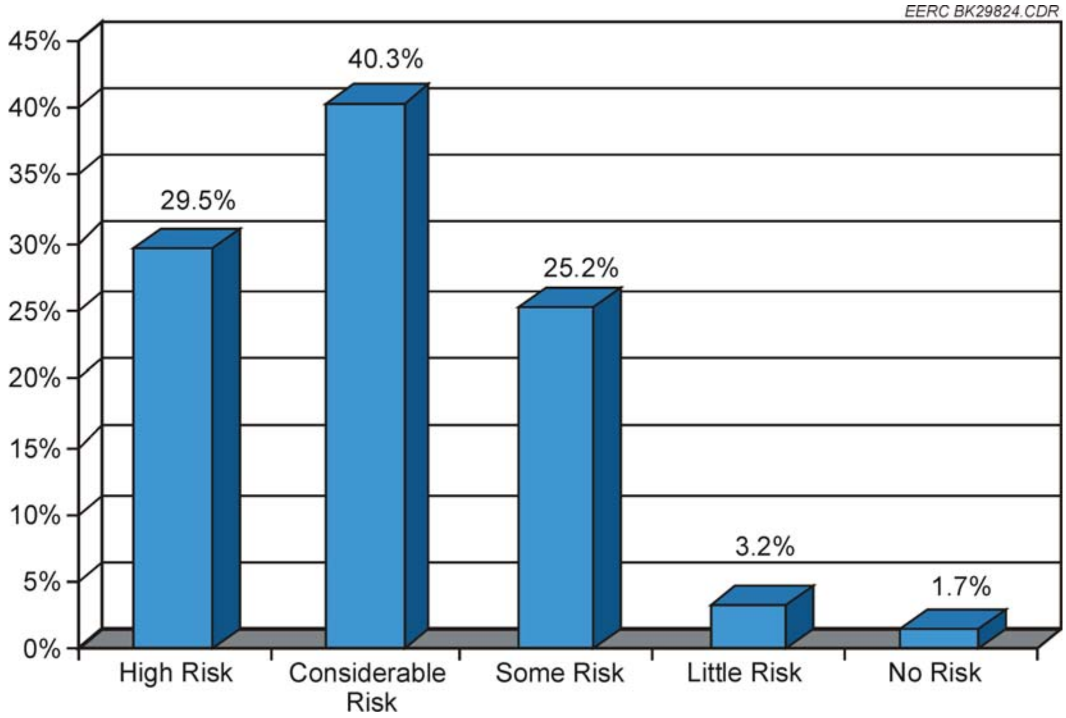


Figure 81. Perceived risk of significant spring flooding in the next 50 years.

systems. In the wake of a devastating flood along the Mississippi River in 1927, the 1936 Flood Control Act shifted flood control responsibility primarily to the federal government and provided a national program for implementing these structural measures (Sheaffer et al., 2002). An evaluation of this program after 20 years concluded that flood damage continued to increase nationally. To create a comprehensive floodplain management program, nonstructural dimensions are needed to supplement the structural measures (Sheaffer et al., 2002).

In order to assess opinion regarding the usefulness of structural and nonstructural measures for flood mitigation, landowners were asked the question, “What do you believe are useful solutions for spring flooding problems in the RRB? Please rate each on a scale of 1 to 5, where 1 indicates very useful and 5 indicate not useful” (see Figures 82 and 83).

The structural and nonstructural measures were combined and reduced to a list of the six most useful flood mitigation measures according to landowners in the RRB. The data were collapsed into a single “useful” category, comprising those who indicated a 1 or a 2 on the scale of 1 to 5. The top five measures are ditch maintenance, stream maintenance, temporary water retention on public land, improving existing surface drainage ditches, restoring natural waterways, and temporary water retention on private land. The top six list, as summarized in Figure 84, consists predominantly of nonstructural measures.

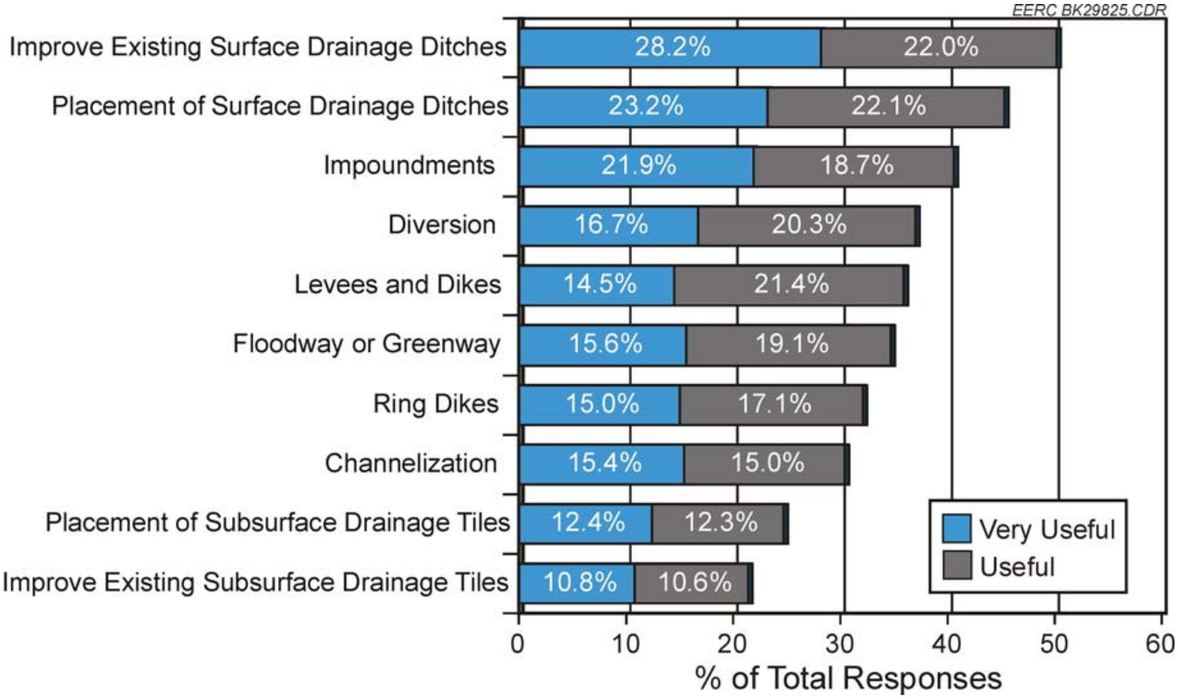


Figure 82. Structural measures.

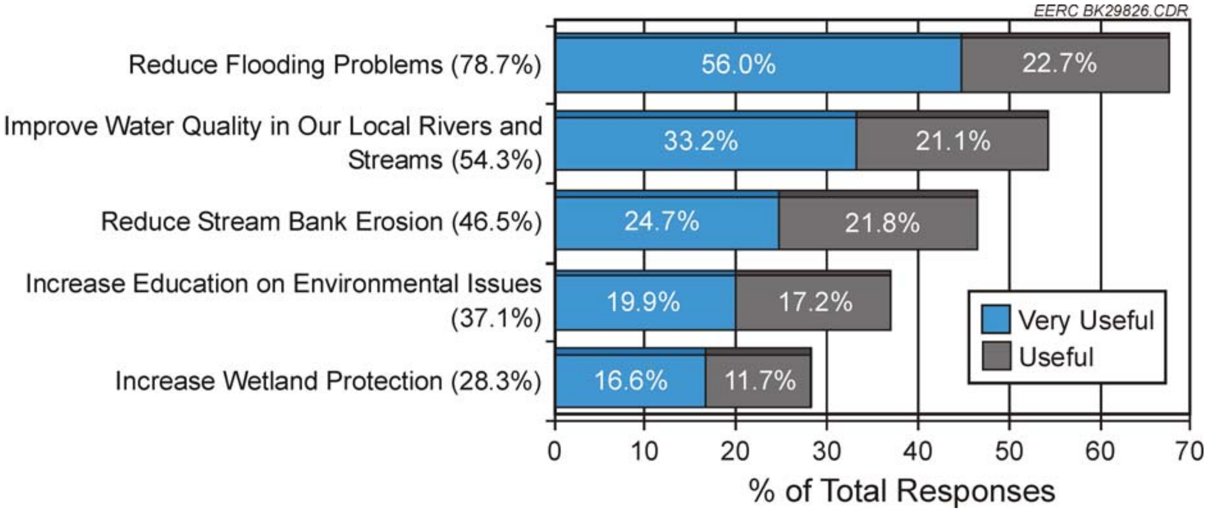


Figure 83. Nonstructural measures.

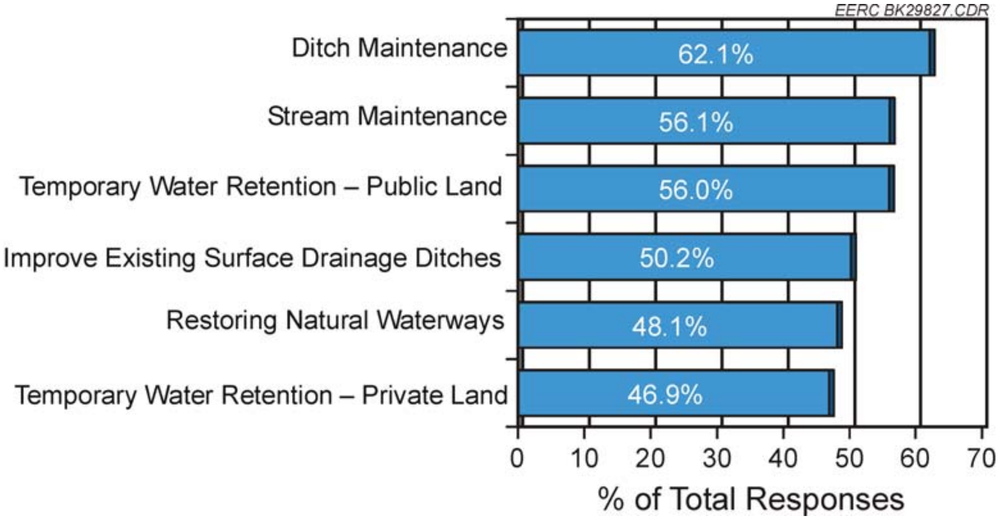


Figure 84. Top six flood mitigation measures identified by survey respondents in the RRB.

Temporary water storage on public land (56.0%) and temporary water storage on private land (46.9%) both encompass the Waffle concept. As such, one could infer that those who find temporary water retention measures useful may also find the Waffle concept to be a useful means of flood mitigation.

3.3.5 Existing Conditions for Landowners

3.3.5.1 Flooding Experiences

Of the respondents, 77.2% have experienced flooding on their land, while 22.8% have experienced no flooding on their land. 56% of the respondents indicated that both spring and summer are seasons of concern for flooding, as listed in Table 26. Various perceived causes for the flooding were given, with nearly 41% identifying overland flooding as the cause of flooding (Table 27). The underlying causes of overland flooding were relatively evenly distributed. Of the respondent sample, 48.4% own land that is adjacent to a river, stream, creek, or drainage system that leads to flooding problems.

Table 26. Basinwide Experiences with Flooding Problems on Their Land

Response	% of Total Respondents
Spring	17.3
Summer	2.6
Both Spring and Summer	56.0
No Problems	22.8
Total	100.0

Table 27. Perceived Non-Weather-Related Causes of Spring Flooding on Their Land

Response/Perceived Cause	% of Respondents Identifying Cause
Overland Flooding	40.8
Culverts Are Sized Wrong	33.5
Neighbor Modifying Runoff Patterns	31.9
Upstream Water Release	26.6
Watercourse Channels Are too Small	32.8
Uncertain of Causes	9.8

Note: Multiple response question, so totaling percentage of responses exceeds 100%.

The "other" category included responses such as dams, beavers, ice jams, and blockage of ditches. Although this study addresses only spring flooding, summer rains were also mentioned as a source of concern for flooding.

3.3.5.2 Holding Back Water

Survey respondents were asked if water had ever been held on their land for any reason, and 18.2% in the basinwide study answered yes. Those respondents were also asked for an open-ended explanation. Reasons offered included beaver dams, natural flooding already occurring on their land, erosion control, wetland and wildlife reasons, planned flood prevention, drainage problems, and water retained by roads. One interesting response was "during the so-called Dirty Thirties, we dammed up any water we could to save water," dating back to times when droughts were a concern and efforts were made to retain soil moisture. Although droughts are not necessarily on everyone's mind now, they will return at some point, as a part of the natural cycle of flooding and drought in the RRB.

3.3.6 Priority Issues in the RRB

A topic covered in the basinwide and nonresponse studies was landowner opinion on natural resource management priorities for the basin. The survey listed five options and asked the respondent to rate them on a scale of 1 to 5, where 1 is a high priority and 5 is a low priority. In the RRB, in rank order, based on summated ranking, the highest priority, as rated by survey respondents, is to reduce flooding problems (78.7%) followed by improving water quality in local rivers and streams (54.3%), reducing stream bank erosion (46.5%), increasing education on environmental issues (37.1%), and increasing wetland protection (28.3%), as seen in Figure 85. Those percentages are derived from combining the high priority (1) and priority (2) into a single ranking of priority. Again, 3 is neutral; 4 is low priority; and 5 is not a priority. The rank ordering was exactly the same for the basinwide and nonresponse group. Percentages reported are for the overall RRB sample.

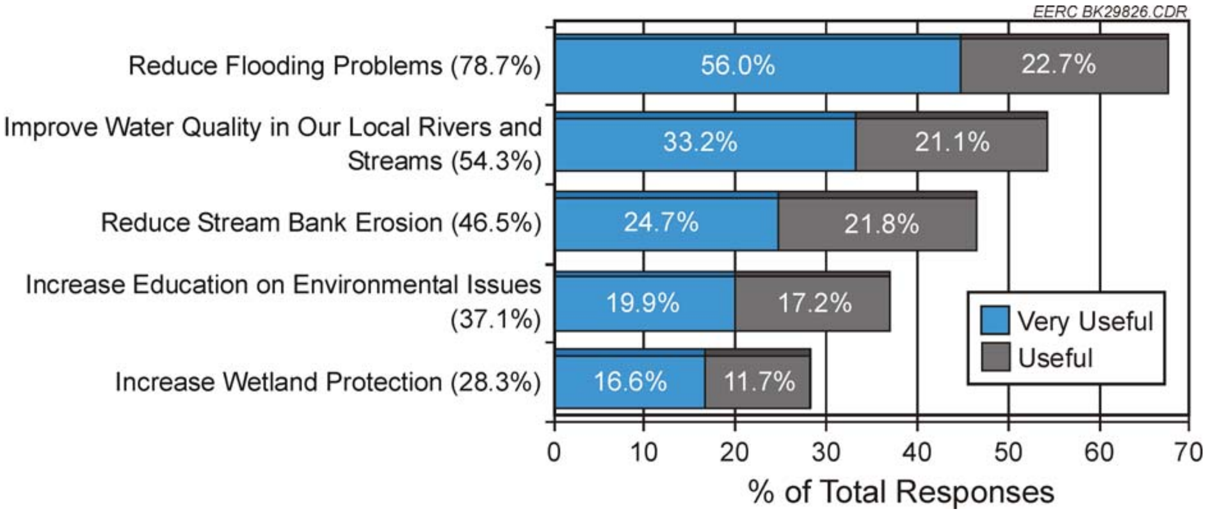


Figure 85. Rank order of priority issues in the RRB.

3.3.7 Information Sources

An ongoing debate in attitude–behavior research involves the relationship of attitudes to behavior and the extent to which, through knowing an individual's attitudes, one is able to predict that individual's behavior. Although the debate has not produced a definite answer or a unified theory, the consensus is that a relationship exists. However, social–psychological research reveals that attitudes, by themselves, are not sufficient predictors of behavior. Other factors need to be examined to understand this relationship. One of the most powerful intervening variables in the attitude–behavior relationship is that of social influences, such as situations, reference groups, and information sources (Petrzelka and Korsching, 1996).

Because of the exploratory nature of the study, a formal relationship between attitudes and information sources or outreach activities was not hypothesized at the outset of the study. The early questions in the survey asked for opinions without addressing the specifics of a potential "temporary water storage program." When survey respondents were asked if they would be interested in learning more about the Waffle study as described toward the latter portion of the survey, 63.4% indicated interest.

Early in the questionnaire, respondents were asked if they had heard or read anything about the Waffle project prior to receiving the survey. Of the total sample, 50.1% had heard of the Waffle concept. They credited the sources presented in Figure 86 as to how they gained information about the Waffle project.

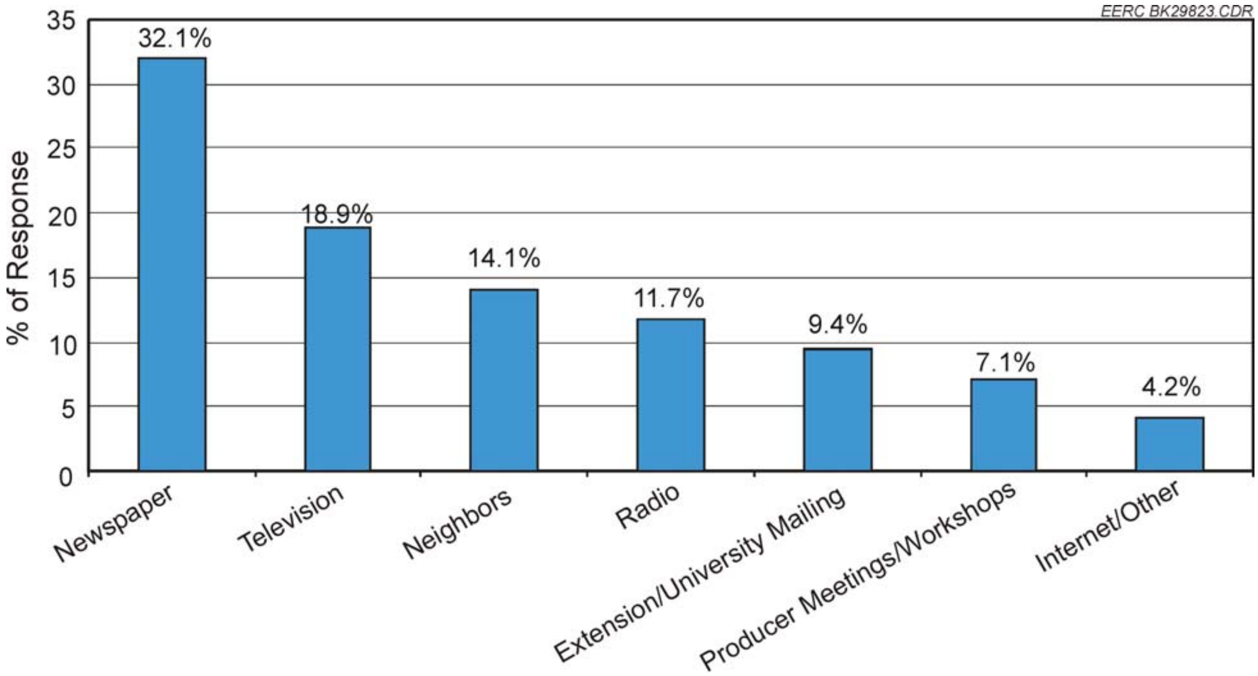


Figure 86. Sources of Waffle information.

3.3.8 Landowner-Generated Opinions for Potential Solutions

As a purely open-ended question, landowners were asked to state what they felt would be a reasonable solution to springtime flooding. Responses ranged from supportive to negative and some were idealistic. The following are some examples of landowner-provided solutions:

- "Maybe (use) tracts of land that are dry and can handle such a runoff."
- "This sounds like a very good-smart idea. Permanent wetland restorations for their added wildlife benefits would be also nice to see."
- "Clean rivers, creeks and dikes so that there are no obstructions" in them.
- "People up here are very set in their ideas. It will take a lot of convincing to change their mindsets. It won't happen overnight…but don't give up trying!"
- "Good ideas for areas that have considerable slope and droughty soil types."
- "A person would have to hold water not just in the spring but during summer months also when flooding would occur."
- "Start by having a water meeting for landowners along the river."
- "Could the waffle plan be used to enhance the capacity or pressure on legal drains?"

- "I believe this waffle concept is a good idea. Utilizing it on marginal land, such as CRP and DNR land, would make the most sense in my opinion."
- "I think it is a good plan, maybe the best. Most other methods (bypass channel, etc.) just pass the problem along to the next location downstream."
- "I think we all need to work together. But I think we need to start many miles both East and West of the Red River to get the best out of the Waffle system. We just can't start at the River and go out."
- "(The) Waffle project will be extremely costly and unnecessary because my neighbors and I have stored water for years at no cost to anyone."
- "Tax anyone adding to water volume. Pay the person who is now holding water and willing to hold more."
- "Should be based on sound science… not out of the mind of environmentalists."
- "The city people need to wake up to reality and instead of complaining about farmers all the time and try to offer solutions and help out."
- "Uncontrollable. Past history shows it."
- "Move to higher ground."

Overall themes for many respondents included the idea of planning and coordination, slowing the rush of water, and utilizing multiple methods to provide solutions and, for others, a sense of loss of control and giving up on the idea of human solutions to the forces of nature.

As stated by Korsching et al. (2001), "interests are largely determined by the perceived benefits and costs of the problem and its resolution, along with the degree to which the existing condition and the perceived change are valued." There is no single public interest on which all residents of a community, township, county, or region will agree.

3.3.9 Willingness to Participate

A key result of the landowner survey was the attitudinal measure of willingness to participate. Potential participation was measured in response to a hypothetical example of the Waffle. The following brief description was provided: "The Waffle project would use both nonagricultural and agricultural land to temporarily store water early in the spring to slow the rate of runoff into tributaries and rivers in the RRB. Initial research that the EERC has indicated that if a Waffle-based program had been implemented prior to the 1997 flood, the severity of that flood would have been substantially reduced. Participation in the Waffle program would be voluntary: however, if water were stored on agricultural land, some minimal planting delays might occur in years when the RRB is subject to widespread flooding. Although it is difficult to predict how often the Waffle would be used or precisely how long water would remain on the land, it is reasonable to anticipate that the Waffle would be used only during years when a major spring flood event is probable and that water storage might last anywhere from a few days to as much as 2 weeks after snowmelt."

In the basinwide study, 46% indicated that they would consider participation, while 24.0% said they would not participate. Thirty percent provided no response to the question (Figure 87). In order to validate the results of the basinwide survey, a second survey was conducted to investigate whether there was a significant difference in those who responded to the initial questionnaire and those who did not. Surveys of opinion often are returned by those with strongly positive and strongly negative opinions, while underrepresenting those who are different or have no strong opinion on the topic. A key question is presented here to demonstrate this effect. In the nonresponse study, the "no" group is consistent at 26.4% (Figure 88). However, the "yes" group is lower at 36.8%. In both surveys, a large proportion had "no response" to the question, 30.1% in the basinwide study, and even higher 36.8% in the nonresponse group. This is likely due to the fact that the Waffle is a novel concept and many of the respondents were not familiar with the concept before the survey. Also, they were presented with a hypothetical scenario of how the Waffle would work if it were ever implemented, so it is not surprising that a proportion would not commit to an opinion on the topic.

EERC BK29821.CDR

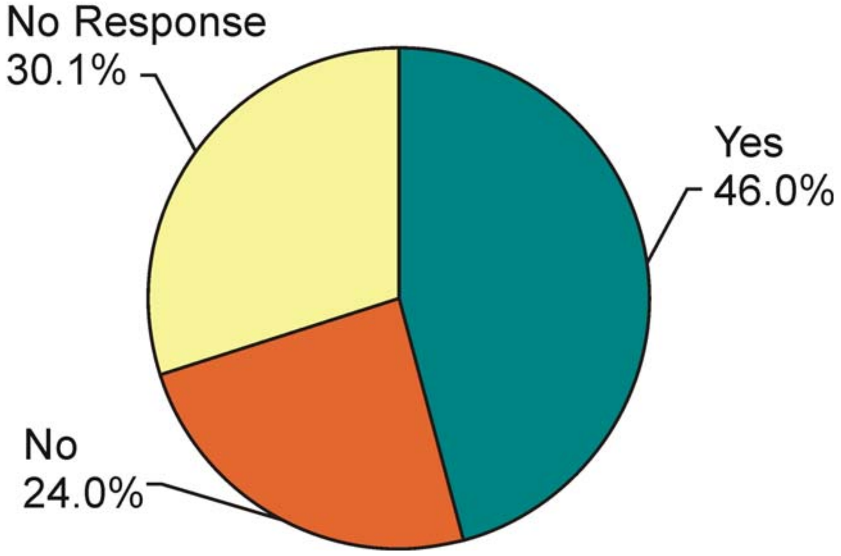


Figure 87. Potential participation basinwide.

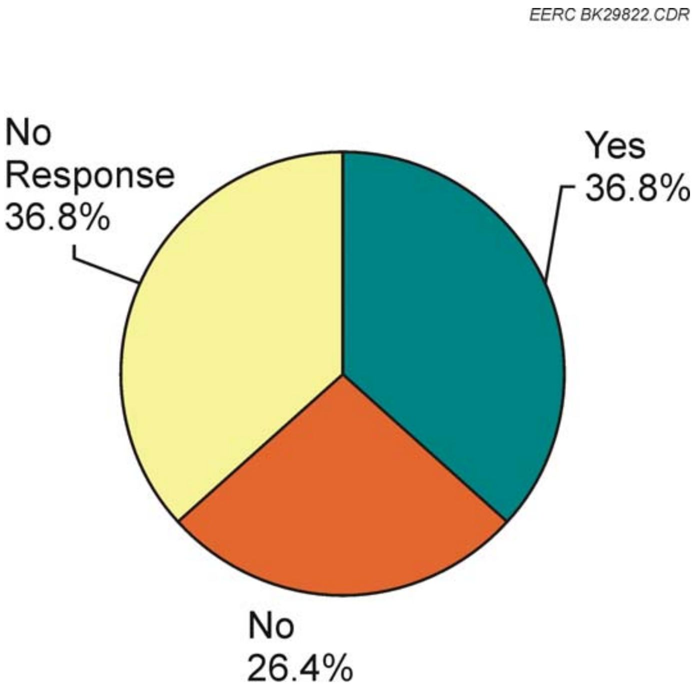


Figure 88. Potential participation in follow-up survey of nonrespondents to basinwide survey.

Considering the difference between the initial basinwide and follow-up basinwide survey groups, one could infer that perhaps those who did not respond to the study in the first place were not as opinionated one way or the other and chose not to respond. The percentage of responses in the no category in both surveys is consistent, suggesting that 24% to 27% of the landowners will not be interested in a new conservation practice, at least initially. This is consistent with the literature on diffusion of innovation (Rogers, 1995) (see Figure 89.) There are the early adopters and innovators, who are first to latch onto a new concept. They serve as the opinion leaders and are willing to try new things. The last group to join is called the late adopters and laggards. People in these groups like to see concepts demonstrated and see the innovators, who are opinion leaders, try them first before they are willing to participate. They are more cautious and take their time in changing their practices and behaviors.

3.3.10 Research on Adoption of New Practices/Innovation

In the 1940s, two sociologists, Bryce Ryan and Neal Gross, published an innovative study on the diffusion of hybrid seed among Iowa farmers which showed how new or innovative practices become adopted. It takes time for landowners to adopt new ideas, and several things need to occur before that happens. First, there is awareness, followed by interest, then evaluation, then trial, and finally adoption.

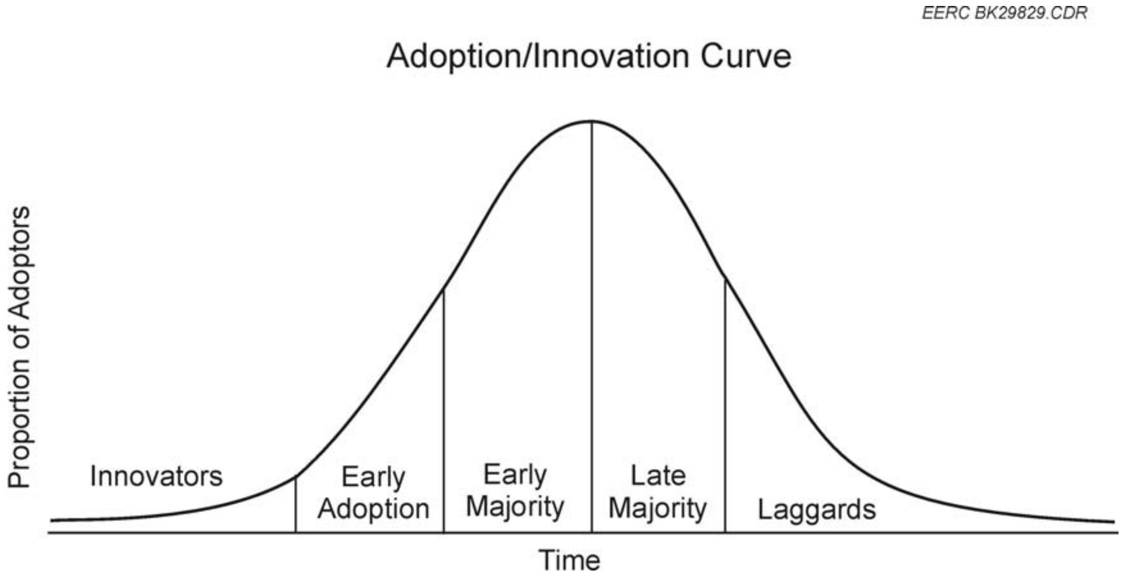


Figure 89. Adoption/innovation curve.

Table 28 shows the progression through the five stages toward adopting something new at different rates (Rogers, 1995). There are the opinion leaders who lead the charge and try something new first. Ryan and Gross classified the segments of Iowa farmers in relation to the amount of time it took them to adopt the innovation, in this case, the hybrid corn seed. The five segments of farmers who adopted the hybrid corn seed were innovators, early adopters, early majority, late majority, and laggards.

"The first farmers to adopt (the innovators) were more cosmopolitan (indicated by traveling more frequently to Des Moines) and of higher socioeconomic status than later adopters." One of the most important characteristics of the first segment of a population to adopt an innovation, the innovators, is that they require a shorter adoption period than any other category.

The hybrid seed corn had many advantages compared to traditional seed, such as the hybrid seed's vigor and resistance to drought and disease. However, there were some barriers to prevent Iowa farmers from adopting the hybrid seed corn. One problem was that the hybrid seed corn could not reproduce. This meant that the hybrid seed was relatively expensive for Iowa farmers, especially at the time of the Depression. Therefore, it is reasonable to assume that, despite the economic profit that the hybrid seed corn brought, its high price made adoption among Iowa farmers slow.

Table 28. Adoption/Innovation Descriptions (Ryan and Gross, 1990; Rogers, 1995)

Category	% of Population	Relationship to Others	Resources	Approach to New Concepts
Innovators	2.5	Venturesome, on their own	Substantial financial resources to absorb possible loss for an unprofitable innovation	Ability to cope with a high degree of uncertainty about an innovation, understand and apply complex technical knowledge
Early Adopters	13.5	Integrated part of the local social system, greatest degree of opinion leadership in most systems, respected by peers	Greatest degree of opinion leadership in most systems, successful	Serve as role model for other members or society in use of new practices
Early Majority	34	Interact frequently with peers, seldom hold positions of opinion leadership		Deliberate before adopting a new idea
Late Majority	34	Pressure from peers	Economic necessity	Skeptical and cautious
Laggards	16	Isolated from peers and possess no opinion leadership	Limited resources	Suspicious of innovations, decision process is lengthy

Experiences from past social science research with landowners, although a different innovation, provide an analogy that is useful in explaining the process that it would take to implement the Waffle with respect to diffusion of innovation and social change and diffusion of the innovation. Rogers is quoted as saying, "One of the greatest pains to human nature is the pain of a new idea." It takes time for change to occur and it starts with the "innovators" and "early adopters." Those are the audiences that are key for implementation of the Waffle or further demonstration of its use. They influence the decisions of the early and late majority to become involved through their social networks.

3.3.11 Group Differences – Interest in Participation

It is helpful to consider the demographics and group differences by comparing the means (averages) of interest in participation. Interest in participation here is reported as a yes/no answer. The results were analyzed using analysis to identify statistically significant differences.

Gender

Male interest in participation was nearly 48%, while female interest was approximately 34%. The overall sample was 46% (Table 29). 29% of women indicated they would not participate, compared to 23% of men. 30% of the population did not respond—29% male and 37% female. A much higher number of respondents (89%) were male.

Years in Basin

The number of years a landowner has lived in the RRB was grouped into two categories, 30 years and less or more than 30 years (Table 30). Of those residing in the basin 30 years or less, 48.4% indicated that they would consider participation while those residing in the basin more than 30 years were at 49.2%. This is not a significant difference. Those who had no response to "years in the basin" were largely absentee landowners, and their interest in participation was considerably lower, with 27.8% indicating "yes" and 57.9% with a no response. The absentee landowner group pulled the overall "yes" level down to 46%. Thus working with landowners who do not live in the RRB presents a considerable challenge to gaining participation.

Acreage

The highest levels of interest in participation by landowners between the standard National Agricultural Statistics Service (NASS) groupings of acreage (Table 31) were found at the highest acreage levels of 1000 to 1999 and 2000+, along with the 1–9-acre group. Landowners with larger acreage were well above the 50% level of interest.

3.3.12 Willingness to Pay

Because of the strong public interest in the project economics, opinions related to compensation as well as willingness to pay were measured. The wording for the questions was

Table 29. Respondent Participation by Gender

Gender	Yes	No	No Response
Male n = 906	47.7%	23.3%	29.1%
Female n = 115	34.1%	29.1%	36.8%
Total	46.0%	24.0%	30.0%

Table 30. Respondent Interest in Participation by Years in Basin

		Yes	No	No Response
Years in Basin	30 years or less	48.4%	24.4%	27.2%
	More than 30 years	49.2%	26.0%	24.8%
	No response	27.8%	14.4%	57.9%
Total		46.0%	24.0%	30.0%

Table 31. Respondent Interest in Participation by Acreage

		Yes	No	No Response
NASS Acres	1–9	55.6%	11.1%	33.3%
	10–49	41.5%	30.2%	28.3%
	50–179	39.7%	28.7%	31.6%
	180–499	43.4%	19.5%	37.1%
	500–999	45.7%	26.4%	27.9%
	1000–1999	57.4%	22.5%	20.1%
	2000+	54.9%	24.6%	20.6%
Total		47.2%	24.0%	28.9%

developed in conjunction with the Agricultural Economics Department at NDSU. The topic of willingness to pay was explored with hypothetical situations. At the time of the study, the Waffle was not at the stage of implementation, so the descriptions are purely hypothetical. The goal was to obtain some ranges on willingness to pay data to utilize in the economic models.

First, an attitudinal question was asked based upon the following brief description of the Waffle.

> "The Waffle project would use both nonagricultural and agricultural land to temporarily store water early in the spring to slow the rate of runoff into tributaries and rivers in the RRB. Initial research at the EERC at UND has indicated that if a Waffle-based program had been implemented prior to the 1997 flood, the severity of that flood would have been substantially reduced. Participation in the Waffle program would be voluntary; however, if water were stored on agricultural land, some minimal planting delays might occur in years when the RRB is subject to widespread flooding. Although it's difficult to predict how often the Waffle would be used or precisely how long water would remain on the land, it is reasonable to anticipate that the Waffle would be used only during years when a major spring flood event is probable and that water storage might last anywhere from a few days to as much as 2 weeks after snowmelt."

The landowners responded on a scale of 1 to 5, where 1 was strongly agree, 2 was agree, 3 was neutral, 4 was disagree, and 5 was strongly disagree; 3 was the neutral response, as found in Table 32.

Later on in the survey, an example was given to derive the "willingness to pay." It was stated as such:

"The following is a hypothetical example to estimate how much it might cost to enroll land in a program like the Waffle. Please consider the following conditions before responding to the question:

- Assume participation in the Waffle is based on landowner bids and would require you to enroll your land for a period of 10 years.

Table 32. Respondent Level of Agreement in Response to a Brief Description of the Waffle Project

Statement	Respondent Mean Level of Agreement*
I would consider enrolling some of my land if compensated in an acceptable manner.	2.75
I would never consider enrolling any of my land in the program.	3.53
I would only consider enrolling if my neighbors also agreed to enroll their land.	3.15
I feel well informed about the Waffle concept.	2.93

* The landowners responded on a scale of 1 to 5, where 1 was strongly agree, 2 was agree, 3 was neutral, 4 was disagree, and 5 was strongly disagree.

- Assume you would receive an initial enrollment payment plus a payment each year that the Waffle temporarily stored water on your land.

- Assume you do not have to enroll all of your land, as only a limited amount of agricultural land in the RRB would be required for the program.

- Assume participation in the Waffle would not affect your coverage in Federal Crop Insurance.

Please note: your bids are not binding; this is just a hypothetical situation.

Given the above example,

Yes, I would consider participation.

a. With a 1-week planting delay, I would need $____/acre to participate.
b. With a 2-week planting delay, I would need $____/acre to participate.
c. With a 3-week planting delay, I would need $____/acre to participate.
d. If I were prevented from raising a crop in a flood year, I would need $____ to participate.

Since this is a feasibility study, the goal was to obtain the average expectations for payment under the hypothetical scenario. Certainly, landowner willingness to pay would differ according to the location and relative value of their land. The average results of the basinwide survey are reported according to all the measures of central tendency (Table 33). The mode is the most frequently occurring answer in the sample, the median is the midpoint value as the mean is the arithmetic average (Table 32). Extreme outliers, such as $10,000 per acre, were eliminated from consideration in the calculations.

The nonresponse group payment request was actually lower on many of the measures of central tendency, as shown in Table 34.

Table 33. Measures of Central Tendency – Basinwide Sample

	1-week Delay	2-week Delay	3-week Delay	4-week Delay
Mode	$10.00	$20.00	$100.00	$100.00
Median	$25.00	$50.00	$70.00	$100.00
Mean	$48.96	$78.68	$117.52	$155.53

Table 34. Measures of Central Tendency – Nonresponse Sample

	1-week Delay	2-week Delay	3-week Delay	4-week Delay
Mode	$20.00	$40.00	$60.00	$100.00
Median	$27.50	$40.00	$60.00	$100.00
Mean	$39.06	$65.00	$91.20	$155.53

It is also useful to consider the measures of dispersion (Table 35 and 36) which include the minimum and maximum values and the standard deviation.

In the nonresponse study, the ranges were not as extreme. No one expected a large reimbursement amount, but also no one was willing to donate their land. That outcome mirrors the interpretation of the findings in the basinwide group. The interpretation is that those that did not respond to the initial survey were neither strong proponents nor strong opponents of the Waffle concept. So, it is expected that this group would fit in the middle of the pack in terms of willingness to consider or adopt innovative water management practices such as the Waffle in the future.

3.3.13 Landowner Survey Conclusions and Recommendations

An approach to flood mitigation, the Waffle concept, would necessitate basinwide social and behavioral change. As indicated by the survey results, if the compensation were reasonable, many respondents were agreeable to the concept. Alluding to potential compensation levels on

Table 35. Measures of Dispersion – Basinwide Sample

	Minimum	Maximum	Mean	Std. Deviation
1 Week	$0	$2000	$48.96	125.48
2 Weeks	$0	$2750	$78.68	165.78
3 Weeks	$0	$3500	$117.52	246.26
4 Weeks	$0	$5000	$155.53	267.65

Table 36. Measures of Dispersion – Nonresponse Sample

	Minimum	Maximum	Mean	Std. Deviation
1-week Delay	$5.00	$250.00	$39.0625	44.1485
2-week Delay	$10.00	$500.00	$65.0000	90.0096
3-week Delay	$15.00	$750.00	$91.2069	135.7956

the landowner survey suggests that if a Waffle Program were ever implemented, a corresponding compensation package would need to be developed. Compensation could be presented as a federal, state, or private insurance program or some combination of all of those possibilities.

Both policy change and social change take time. In response to the flood of 1997, traditional approaches to dealing with a drastic flood took place with the assistance of FEMA and USACE. Now, 10 years later, in 2007, structural measures in response to that flood event in the greater Grand Forks area are nearly complete. However, not all of the RRB has reached that point. The Waffle concept could still be utilized to augment any existing measures. From the survey results, there is certainly enough social support demonstrated to set the stage for Waffle implementation throughout the Red River Valley in the future.

The results of this survey provide implications for other projects. First, floods and droughts are not unique to the RRB. Therefore, other flood-plagued regions of the world, where permanent measures are not yet in place, could benefit from the findings here. Secondly, the landowner survey results, in more general terms, are indicative of landowner propensity to change for the greater good. These findings provide the groundwork for other studies and projects in related areas, such as conservation practices. Both the watershed-level and the basinwide survey could be used as background in launching future projects that require social change.

3.4 Discussion of Implementation Options

Both government incentive and cost-share programs and market-based approaches can be used to fund the implementation of the Waffle on a landscape scale. Government subsidy programs include the farm bill conservation programs, such as the Environmental Quality Incentive Program (EQIP), CRP, and the Conservation Security Program (CSP) which was established under the 2002 farm bill. EPA water quality programs and/or FEMA may also provide a source of funding for the cost of structural modifications necessary to implement the Waffle. Market-based approaches include possible contracts with insurance companies or other private, public, or nonprofit entities for the provision of ecosystem services. The following summary of federal programs and ecosystem source markets was provided by Andrew Manale, a Senior Policy Analyst at EPA and temporary consultant on the Waffle project.

3.4.1 Federal Programs

Although sufficient funds could at least in the short-term be made available through government programs to implement the Waffle, the prognosis for long-term funding in sufficient amounts is highly uncertain. For example, although USDA entitlement programs (such as CRP) are not supposed to be dependent upon annual congressional appropriations for funding, the reality is that Congress has, in most years, chosen to limit the amount of funds available for these programs.

The overall goal of CRP is to reduce sediment loss from farmlands and to improve water quality (Natural Resources Conservative Service, 2007). CRP could be one means of paying for Waffle storage on agricultural land through the establishment of easements to allow temporary water storage. However, there are a number of important caveats that should temper reliance upon this route: administrative limits on how much agricultural land in a county can be put into CRP and North Dakota statutory restrictions on permanent easements on agricultural lands. Moreover, retiring lands may not be the most cost-effective approach to achieving desired levels of water storage, even without considering the social cost of taking lands out of production and, hence, the reduction in revenue to local communities. The premise of the Waffle concept is that agricultural land can, in nearly all flood years, temporarily store flood water and produce crops, allowing for a continuing stream of revenue to these communities.

EQIP can pay for conservation practices on working lands under 10- or even 15-year contracts. It is best used as a transition program, especially where there are, despite short-term costs, long-term benefits to agricultural producers and landowners to more permanent adoption of management practices. This is because EQIP does not fund the maintenance of practices beyond the contract period. However, as currently implemented, EQIP is a program that meets individual landowner needs, particularly with regard to water quality, not necessarily the needs of watersheds or larger landscapes related to flood mitigation. Its primary focus has been practices that contribute to water or soil quality improvement or provide wildlife habitat. Flood mitigation has not been a priority, even if, in so doing, the purposes of water quality are served, and funding has generally not targeted specific locations within a watershed. Moreover, language in the 2002 farm bill has been interpreted by USDA to forbid the targeting of EQIP funds to specific geographic areas.

Use of EQIP funds, as well as conservation funding in general, would require designation by the State Technical Committee, established under the auspices of USDA NRCS, of the Waffle approach as an approved practice. Showing the contribution to water quality improves its likelihood of acceptance and funding. The process for approval can be set in motion by appeal to the committee.

The Waffle requires a very large number of culvert modifications across a large number of watersheds within the RRB to have a significant impact on the kind of flood stages that occurred in 1997. USDA cost-share programs are generally not targeted or utilized in a focused manner or as a watershed or landscape-scale approach. Instead, they are implemented as assistance programs to farmers who request the funds for which approval is granted on a case-by-case basis.

The resolution to this problem may be in targeting drainage systems that are subject to frequent repair or significant maintenance. The administering agency for the Waffle coordinate with the State Technical Committee, which reviews the needs assessment for USDA-supported cost-share funds to seek conservation funding for those portions of watersheds that undergo frequent road and/or culvert repair and would be suitable for Waffle-type culvert modification. A similar approach could also be used with FEMA funds. In many cases, the funding to repair roads and restore culverts damaged by floodwater is provided by FEMA. Although FEMA is designed to provide funding to communities after major natural disasters have already occurred, it also supports "cost-effective measures that would reduce or eliminate the threat of future damage to a facility damaged during the disaster" (Adjusters International Inc., 2006). This hazard mitigation funding may be a means of providing support to outfit existing culverts with flow control devices, thereby mitigating flood damage to downstream roads.

CSP is “a voluntary program that provides financial and technical assistance to promote the conservation and improvement of soil, water, air, energy, plant and animal life, and other conservation purposes on Tribal and private working lands. Working lands include cropland, grassland, prairie land, improved pasture and range land, as well as forested land that is an incidental part of an agriculture operation” (Natural Resources Conservation Service, 2007). Although CSP is implemented on a watershed basis, the watersheds are generally the size of the subwatersheds of the RRB (such as the Maple and Wild Rice Rivers). CSP is an entitlement program open to all farmers who qualify for the program. Funding is currently by watershed, which must be accepted for funding through a competitive solicitation. Farmers in each watershed within the RRB or at least those that have been identified as potentially providing the most flood storage through the Waffle could receive an additional payment through CSP, provided that they allow for the structural modifications necessary for temporary water storage. A longer-term horizon for implementation of the Waffle could provide for modification of culverts in each watershed if chosen for CSP funding.

Alternatively, the role that temporary water storage plays in protecting water quality could be emphasized with funding approved for the Waffle as an approved agricultural drainage practice to address water quality concerns resulting from storm water runoff. For this to occur, Waffle practices would have to be listed by NRCS as an approved practice or activity to address the resource problem or issue under its Field Office Technical Guide (FOTG) standards. Rules do allow for approval of interim conservation practice standards and financial assistance for pilot work to evaluate and assess the performance, efficacy, and effectiveness of the technology or conservation practice or activities (www.nrcs.usda.gov/programs/csp/pdf_files/ cspruleamend62905.pdf.). Waffle culvert modification potentially falls under the enrollment category and criterion for land use, cropland water quality—stewardship practice and activity list for water quality. It could potentially qualify as a “Drainage water management through seasonal on-farm water storage and retention.” (Federal Register, 2005).

The only program that has been implemented as a partnership program with another government entity on a targeted basis has been the Conservation Reserve Enhancement Program, or CREP, a cost-share land retirement program with states. CREP, which is administered by USDA’s FSA, is a community-based program conducted as a partnership among producers; tribal, state, and federal governments; and, in some cases, private groups (www.fsa.usda.gov/pas/publications/facts/html/crep03.htm). CREP addresses high-priority conservation issues of both local and national significance. On a local level, because flood mitigation has been of such high importance, temporary water storage on CREP acreage to reduce flooding is an approved practice. Contracts require a 10–15-year commitment to keep lands out of agricultural production; however, as stated earlier, land retirement may not be the most cost-effective approach in implementing the Waffle.

3.4.2 Federal Grant Programs

If the environmental benefits of the Waffle, such as reduced soil erosion and improved water quality, were a driving mechanism for implementation, then there are EPA grant programs that could serve as potential funding sources. The Targeted Watershed Grants Program is designed to encourage successful community-based approaches and management techniques to protect and restore the nation's waters. It is a competitive grant program based upon collaboration, new technologies, market incentives, and results-oriented strategies. Eligible projects are watershed-based, on-the-ground activities to attain water quality standards, protecting and restoring the natural and beneficial uses of floodplains and improving water resources. Watershed nominations must be submitted by either a governor or a tribal leader. Other potential EPA grants (see http://cfpub.epa.gov/fedfund/) include the Flood Mitigation Assistance program that can pay for erosion control and drainage improvements, Nonpoint Source Implementation Grants (319 Program) to pay for installation of best management practices (BMPs), and Water Quality Cooperative Agreements to promote the coordination of environmentally beneficial activities. Communities and watershed groups are eligible to apply.

3.4.3 Market-Based Approaches

3.4.3.1 Insurance

The use of an insurance-based approach to implement the Waffle is also a potential mechanism to fund implementation. Recent (FY2000) legislative amendments to USDA's crop insurance program allow for the development of federally subsidized crop insurance policies where the use of the policy can be shown to encourage sustainable agricultural practices. Crop damage associated with temporary water storage on agricultural lands to avert damages associated with downstream flooding can qualify for the program, according to Stephanie Mercier, Chief Economist to the ranking member of the Senate Agriculture Committee. The legislation allows for coverage of the costs associated with developing the insurance policies.

To utilize the federal crop insurance program, a request would most likely have to be made to the USDA RMA to modify or clarify the regulatory guidance that covers crop insurance entitlement and compensation. The biggest hurdle arises when storage is necessary before the final planting date. A farmer will likely expect compensation for a reduction in yield below the optimum. Most private insurers that issue crop insurance under the federal crop insurance program would likely hesitate to cover cropland covered by the Waffle because of the concern about increased risk of payouts without expressed guidance by RMA. The solution may be for the Waffle administering agency to provide a guarantee to cover those outlays by private insurers that are not covered by the federal program for losses in cases of extreme flood risk.

3.4.3.2 Markets in Ecosystem Services

Temporary water storage on agricultural lands can serve to restore an ecosystem service that the land provided before conversion to agricultural production. There is growing interest in developing markets for these services that provide not just an alternative income stream to landowners and farmers but also cost-effective alternative means (as opposed to conventional capital-intensive structural approaches) for providing goods and services and private benefits to communities, private entities, and businesses. New tools create new opportunities to identify and quantify these goods and services, to identify the beneficiaries, and to quantify their benefits (www.naturesservices.org).

Markets in ecosystem services require a clear and quantifiable definition of the service, measurability, and a mechanism for enforcement. Potential beneficiaries—in this case, downstream urban communities and businesses—may be willing to pay upstream farmers and land managers for managing their lands in a way that reduces downstream environmental risks or damages, such as flooding. USDA or other federal or state agency funds could be used to underwrite a portion of the costs that exceed the direct benefits to private entities.

4.0 ECONOMIC EVALUATION

4.1 Introduction

One of the key goals of the Waffle project was to determine if distributed, basinwide storage is a cost-effective means of mitigating large springtime floods. Because conventional flood mitigation projects, like dikes and diversions, typically focus on providing protection for one location within a watershed, the cost associated with a basinwide approach to flood mitigation had never been evaluated. One of the benefits of the Waffle concept is that the flood mitigation effect is achieved through utilization of multiple, small-scale storage areas; therefore, large-scale structural modifications can be avoided, runoff can be controlled before it becomes a problem, and the failure of one storage parcel would hardly result in widespread devastation. However, because of the distributed nature of the storage and its effects, as well as the number of storage sections involved, the economic evaluation of the concept was more complex and encompassed a wider range of variables than typically required for analysis of conventional flood mitigation measures.

To evaluate the economic feasibility of the Waffle concept, the EERC subcontracted three economists from NDSU to conduct a first assessment of the cost-effectiveness of the Waffle to mitigate springtime flood damages in the RRB. The specific objectives of their evaluation were to:

1) Estimate the costs of maintaining and operating the Waffle.

2) Estimate the mitigated flood damages (benefits) from the Waffle.

3) Estimate the benefit–cost ratio of the Waffle over a reasonable range of physical and economic values.

The detailed results of the economic evaluation are summarized in Bangsund et al. (2007), which is included as Appendix H of this report. The following is a summary of the economic evaluation methodology, results, and conclusions.

4.2 Economic Evaluation Overview and Results

The cost estimates of the Waffle included the estimated expenses for structural modifications and maintenance of the storage sites; landowner reimbursements, including retainer payments and a water storage payment in the event that storage is needed (based on

10-year contracts); administrative cost; and enrollment expenses. The payment acreage numbers were provided to NDSU by the EERC and included a minimum, moderate, and maximum acreage estimate. As described in Appendix H, these estimates included the flooded acreage plus the additional land that may be inaccessible because of the water storage and, therefore, could be subject to planting delays.

The cost estimates were extended 50 years into the future and adjusted for inflation accordingly. Three cost scenarios were evaluated—a baseline scenario, plus an optimistic and pessimistic scenario. The key variables that were adjusted between the baseline, optimistic, and pessimistic cost scenarios were enrollment expense, retainer payment, water storage payment, maintenance, administrative expenses, and inflation rates. For the baseline scenario, values for key economic variables included $1500 per section for enrollment expenses, retainer payments equal to 120% of cash rent, water storage payment rates equal to 175% of cash rent, maintenance costs equal to 1% of the value of culvert control devices, administrative expenses starting at $250,000 per year with an additional $2 for every 100 acres enrolled, and an annual inflationary rate of 2.75%. The present value costs for the full-scale Waffle (100% of storage estimates) in the baseline scenario ranged from $543 million with maximum payment acreage estimates to $208 million with minimum payment acreage estimates, assuming the Waffle was implemented and in place from 2006 to 2055.

The benefits of the Waffle were evaluated in terms of the damage that could be mitigated at several key points along the Red River during major springtime floods. To estimate damage costs as a function of river stage, flood stage/damage functions were obtained from the USACE. Three population projections were used to adjust the damage values in the flood stage/damage functions for future population changes in the study communities, referred to as the pessimistic, baseline, and optimistic population scenarios. To determine the potential mitigated flood damage, the EERC provided the estimated stage reductions for Wahpeton–Breckenridge, Fargo–Moorhead, Grand Forks–East Grand Forks, and Drayton as a result of implementing 100% and 50% of the moderate and conservative Waffle storage estimates. These results are discussed in detail in Section 2.4 of this report. The present value of the gross benefits of the Waffle ranged from $605 million with 50% of the conservative Waffle storage capacities under the baseline population scenario to $915 million with 100% of the moderate Waffle storage capacities.

The net benefits of the Waffle were calculated by subtracting the Waffle costs by the gross benefits. Under the baseline population scenario, net benefits of the Waffle were positive across all cost, scale, and water storage situations except one. Within the baseline population scenario, as expected, net benefits across all combinations were highest with the optimistic cost scenario and lowest with the pessimistic cost scenario. In the baseline cost scenario, net benefits with the full-scale (i.e., 100% of estimated storage volumes) Waffle were estimated to range from over $700 million with moderate water storage combined with minimum acreage to about $125 million with conservative water storage combined with maximum acreage (Table 37). When costs were reduced in the optimistic cost scenario, net benefits were estimated to range from about $760 million with moderate water storage combined with minimum acreage to nearly $266 million with conservative water storage combined with maximum acreage. An increase in costs found with the pessimistic cost scenario produced net benefits which ranged from $627 million with moderate water storage combined with minimum acreage to a negative net

Table 37. Net Benefits of the Waffle, Baseline Population Scenario, 2006 through 2055 (full-scale Waffle refers to 100% of estimated storage volumes, while half-scale Waffle refers to 50% of estimated storage volumes)

	Full-Scale Waffle		Half-Scale Waffle	
Cost and Acreage Scenarios	Moderate Water Storage	Conservative Water Storage	Moderate Water Storage	Conservative Water Storage
	------000s------			
Baseline Cost Scenario				
Minimum Acreage	706,859	460,295	703,665	497,590
Moderate Acreage	552,599	306,035	626,832	420,757
Maximum Acreage	371,750	125,186	536,124	330,049
Optimistic Cost Scenario				
Minimum Acreage	759,051	512,487	730,714	524,639
Moderate Acreage	645,253	398,689	674,051	467,976
Maximum Acreage	512,069	265,505	607,243	401,168
Pessimistic Cost Scenario				
Minimum Acreage	627,464	380,900	662,135	456,060
Moderate Acreage	419,918	173,354	558,732	352,657
Maximum Acreage	176,188	(70,376)	436,497	230,422

benefit (cost) of $70 million with conservative water storage combined with maximum acreage (Table 1). In most of the scenarios, the averted flood damages from Fargo/Moorhead accounted for 80% or more of the economic benefits.

The results of the economic analysis suggest that the Waffle could offer significant economic benefits if used to mitigate large spring floods for the major cities of the RRB, particularly Fargo/Moorhead. It is important to note that the potential environmental benefits and flood mitigation benefits to smaller communities, farmsteads, and rural infrastructure and agricultural land were not included in this study; however, mitigation of these damages could be significant. For example, during major spring floods, it is not uncommon for individual counties to spend upwards of $1 million to repair damaged roads. Plus, most landowners and/or producers are powerless to prevent their fields from being flooded from upstream runoff. The Waffle could provide a means of reducing unintentional flooding of agricultural land while providing payments to landowners that agree to temporarily store water on their land. In addition, potential ancillary benefits could be significant, such as reduced sediment transport in the RRB waterways, and increased soil moisture and aquifer recharge during droughts.

5.0 CONCLUSIONS

The results of this study indicate that the Waffle concept is technically, socially, and economically viable as a means of mitigating damage from large springtime floods and providing a necessary augment to conventional flood protection measures. The Waffle approach also offers a means of mitigating major flood damage for those areas with little or no existing protection, such as agricultural land, farmsteads, and smaller communities. Given the history of flooding in the region, the Waffle offers the long-term security from floods needed to sustain the economic viability of the region.

The basinwide flood reduction benefits discussed in this report could be achieved by using only 1.5% to 5.3% of the land area in the RRB **without taking agricultural land out of production**. However, the Waffle concept need not be implemented on a basinwide scale to have benefits. The Waffle study results indicate that localized benefits can be achieved from temporary Waffle storage. Because this approach reduces overland runoff and flows in ditches and waterways downstream of storage areas, localized damage such as road washouts and unintended flooding of agricultural land could be avoided. During major spring floods, it is not uncommon for individual counties to spend upwards of $1 million on road damage (Grand Forks County Highway Department, personal communication, 2006). Considering the frequent and recurring nature of major floods in the RRB, those road damage costs are very significant. In addition, a major point of contention among rural landowners and farmers is the flooding of their land by upstream drainage. In most areas, the landscape is drained as rapidly as possible by each landowner without the broader context of upstream and downstream drainage activities. In many cases, this uncoordinated approach to drainage results in the springtime runoff rapidly accumulating to adversely impact downstream landowners and communities. The Waffle could help reduce some of these issues since the drainage would be coordinated on a subbasin and basinwide scale.

By providing controlled, temporary water storage, the Waffle not only slows springtime runoff rates, but also reduces total flood volumes. The results of the field trial showed that an average of 38% of the total stored water volume can be lost to infiltration and evaporation, thereby reducing the total volume of potential floodwaters that would have otherwise flowed downstream. Infiltration of the stored water could also provide a benefit during dry years by increasing soil moisture and replenishing depleted groundwater supplies, especially in soils with higher permeability. Although not every participant in the Waffle, if implemented, may take advantage of the potential water storage benefits during drought years, the infrastructure would be in place to do so.

Waffle storage could also help reduce sediment erosion from farmland and within waterways as a result of lower and more controlled peak flows. Recently, there has been increased agreement among water resource managers, scientists, and state and federal agencies over the need to reduce extreme flows in the Red River and its tributaries because of concerns over high suspended-sediment concentrations. High sediment loads can adversely impact aquatic ecosystems, plus potential contaminants such as phosphorus and pesticides often adhere to sediment particles. Many of the waterways in the RRB are currently listed by EPA as “impaired” because of high sediment concentrations, and eutrophication problems in Lake Winnipeg have led the IJC to recommend a 10% reduction in phosphorus loading at the international border. Since the highest sediment-loading rates occur during springtime flood events, the Waffle approach could be an effective means of reducing sediment erosion while keeping agricultural land in production.

Hydrologic modeling conducted through this study indicates that the Waffle approach is particularly effective as a means of intercepting and controlling overland runoff and, as such, offers an excellent complement to on-channel dams, dikes, or diversions, which address channel flow, not overland runoff. And unlike structural measures, the Waffle approach does not entail implementing drastic structural measures to intercept, retain, or divert large volumes of water in order to achieve rural and urban benefits. Instead, minor structural modifications are made to the existing culverts, and the stored water is primarily that which fell directly on the storage parcels.

Results of the economic analysis conducted by NDSU indicate that significant financial benefits could be achieved if the Waffle were implemented to mitigate severe springtime floods. It is interesting to note that the baseline cost scenario evaluated by NDSU assumed a landowner reimbursement rate equivalent to 175% of cash rent and a signing bonus equivalent to 125% of cash rent. Considering that, in all likelihood, agricultural land would still be planted and the landowner/producer would harvest a crop, this could provide a means of supplementing the income of producers/landowners during major flood years while still averting hundreds of millions, if not billions, of dollars in flood damage. It would also help reduce the socioeconomic stress that occurs with devastating floods. When compared to the basinwide landowner survey conducted through the Waffle study, the landowner reimbursement costs used by NDSU are in the range of those reported by survey respondents in order to participate in a Waffle-type program.

There are several ways in which the implementation of the Waffle concept could be funded on the landscape scale, including government incentive and cost-share programs, as well as market-based approaches. Government incentive programs include the farm bill conservation programs, such as EQIP, CRP, and CSP, established under the 2002 farm bill; however, because land enrollment in these programs is limited, they could only be used to fund a portion of the Waffle storage needed to achieve basinwide benefits. Of these federal programs, CRP may provide the fastest and most socially acceptable means of implementing the Waffle in the region. The program guidelines now allow water storage as an acceptable practice on CRP acreage, and many landowners and producers in the region are supportive of water storage on their CRP acreage. In addition, FSA, which administers CRP, has expressed strong interest in using CRP acreage for temporary water storage as a means of mitigating flooding within the state.

Certain federal agencies such as FEMA may also be a mechanism to fund Waffle implementation. Although FEMA is designed to provide funding to communities after major natural disasters have already occurred, it also supports “cost-effective measures that would reduce or eliminate the threat of future damage to a facility damaged during the disaster” (Adjusters International Inc., 2006). This hazard mitigation funding may be a means of providing support to outfit existing culverts with flow control devices, thereby mitigating flood damage to downstream roads.

In addition to federal agencies and programs, market-based approaches to support Waffle implementation may include funding by insurance companies or through private, public, or nonprofit entities for provision of flood mitigation services. For example, large insurance companies may be interested in supporting Waffle implementation since reductions in insurance and disaster payments because of rural and urban flooding may justify the expense of a preemptive countermeasure to mitigate potential flooding.

Ultimately, the best means of implementing the Waffle concept, technically, socially, and economically, will be determined by policy makers, stakeholders, and those entities involved in water management. Because the Waffle can mitigate localized flood damage and need not be implemented on a basinwide scale, it allows for flexibility with implementation guidelines and policies, which can be developed to best suit the needs of participants and beneficiaries in a particular region.

5.1 Additional Benefits of the Waffle Study

Although the main goal of the Waffle project was to evaluate a specific flood mitigation concept, the information and tools developed through the project have multiple benefits above and beyond the study. Some of the key tools developed through this project include the following:

- Development and calibration of hydrologic models using SWAT for 27 of the 28 watersheds in the U.S. portion of the RRB. *At this time, this is the largest detailed modeling effort of its kind in the United States.* These models can be used to investigate the effects of a variety of structural and nonstructural flood mitigation practices and/or land management practices on water quantity and water quality throughout the RRB. This is the first time that tools of this magnitude and utility are available for the RRB. They will provide us with insight on some of the most important water-related issues in the RRB, including the following:
  - How much would severe droughts impact surface water and groundwater supplies as well as surface water quality?
  - How much are individual watersheds and subwatersheds contributing to sediment and nutrient loading in the waterways of the region and, if BMPs were implemented, how much could water quality be improved?
  - What combination of flood mitigation options and/or land management practices is optimal for achieving the largest downstream reduction in peak flows?
- Development and calibration of a main stem hydraulic model of the Red River using HEC–RAS.[1] This model can be used to evaluate the impact of tributary flow reductions on Red River flood stage. This is the first detailed un-steady-state model developed for the Red River.
- Creation of an interactive, online database containing natural resource-related metadata for the RRB. This database can be queried based on political boundaries, such as counties or states, by watershed, and/or by data category or type. Links to online data are provided.
- Development of an interactive, online literature database containing over 400 references related to RRB flood protection. Users can search for references based on key word, title, or author. Query results include the full citation and article abstract (if available).

---

[1] The U.S. Army Corps of Engineers developed the HEC–RAS model upstream of Halstad. The EERC expanded the model from Halstad to Emerson, Manitoba.

- Compilation of landowner/producer opinions regarding flooding and the most socially acceptable means of flood mitigation. These results could help guide future flood mitigation planning throughout the RRB.

5.2 Recommendations for Future Work

The goal of this study was to evaluate the feasibility of the Waffle concept. Because the results indicate that it is, indeed, technically, economically, and socially feasible, if stakeholders and policy makers decide to pursue implementation of the concept, there are several steps that should be taken to facilitate implementation:

- The economic evaluation of the Waffle concept focused on the flood reduction benefits for larger cities and communities along the Red River because there is a lack of flood damage cost data for rural areas and smaller communities. However, the technical results of this study indicate that flood mitigation benefits to rural areas, farmsteads, and smaller communities could be substantial. An evaluation of the economic benefits of the Waffle to rural areas is needed, especially since implementation of the Waffle at the local level may be more desirable and more manageable than basinwide implementation.

- There are several efforts under way to collect high-resolution digital elevation data for the RRB using Lidar. This would be extremely useful for quickly and efficiently evaluating the storage volume of potential Waffle storage sections and mitigating the need for time-consuming GPS surveys of each site. In addition, it would allow for delineation of the flooded and nonflooded portions of Waffle storage sites, which would help establish landowner reimbursement rates, especially on sections with multiple landowners.

- A digital, basinwide culvert inventory is needed to better evaluate the localized impacts of the Waffle. These data, coupled with detailed elevation data, could be used to identify locations where infrastructural damage and flooding of agricultural land could be minimized and better model the localized flood reduction impacts of the Waffle.

- One of the key benefits of this study was the development of hydrologic models for each of the RRB's subwatersheds (except Devils Lake) using SWAT and the development of a hydrodynamic model of the Red River using HEC–RAS. The SWAT models could be further expanded by validation with flood events other than those investigated, especially for more recent flood events. The HEC–RAS model, which was calibrated for the 1997 flood, could also be calibrated and validated for other flood events. This would allow for evaluation of the Waffle, as well as any other type of flood mitigation practice (i.e., on- and off-channel dams, retention ponds, restored wetlands), over a broader range of flood events and melting conditions.

- Now that a comprehensive, detailed model has been developed for the entire RRB using a consistent framework, this tool can and should be used to evaluate a variety of water management strategies to support basinwide flood and drought planning, water quality improvement, and sustainable water use.

- Throughout this study, much public input was gathered regarding general concerns and/or suggestions pertaining to the Waffle concept and, ultimately, this input helped shape the direction of this study. However, because this was a feasibility assessment and the details of implementation and landowner compensation were not established, little public input was gathered with respect to the most socially acceptable means of program implementation (i.e., suggested length of contract periods). Given that Waffle implementation would require widespread social change, additional public input should be obtained in this area to ensure reasonable public acceptance of the program guidelines and contracts.

7.0 REFERENCES

Adjusters International, Inc., 2006, Disaster recovery today—FEMA recovery issues for decision makers and leaders: Utica, New York, Adjusters International, Inc., Issue 06.

Bangsund, D.A., and Leistritz, F.L., 2004, The economic contribution of the sugar beet industry in Minnesota, North Dakota, and Eastern Montana: Agribusiness and Applied Economics Report 532, www.crystalsugar.com/coopprofile/coop1.economics.asp (accessed May 2007).

Bluemle, J.P., 1997, Factors affecting flooding in the Red River Valley, in Proceedings of the North Dakota Academy Science: v. 51, no. 1, p. 17–20.

BlueStem Incorporated, 1996, An evaluation of the Create-A-Wetland Program: Report to North Dakota Wetlands Trust Board of Directors, 1996.

Brooks, G.R., St. George, S., Lewis, C.F.M., Medioli, B.E., Nielsen, E., Simpson, S., and Thorleifson, L.H., 2003, Geoscientific insights into Red River flood hazards in Manitoba: Geological Survey of Canada, Ottawa, Open File Report 4473, 35 p.

De Laney, T.A., 1955, Benefits to downstream flood attenuation and water quality as a result of constructed wetlands in agricultural landscapes: Journal of Soil and Water Conservation, v. 50, no. 6, p. 620–626.

Dyhouse, G.R., 1995, Myths and misconceptions of the 1993 flood, www.mvs.usace.army.mil/dinfo/pa/fl93info.htm (accessed July 2006).

Federal Emergency Management Agency, 2003,

Federal Register, 2005, Department of Agriculture Natural Resources Conservation Service Notice, v. 70, no. 57, March 25, 2005, p. 15281–2, http://a257.g.akamaitech.net/7/257/2422/01jan20051800/edocket.access.gpo.gov/2005/05-5895.htm (accessed May 2007).

Gerla, P.J., 1992, Pathline and geochemical evolution of ground water in a regional discharge area, Red River Valley, North Dakota: Ground Water, v. 30, no. 5, p. 743–502.

Halliday, R., and Jutila, S., 2000, Hydrologic and hydraulic modeling in the Red River Basin—a report of the Tools Group: International Red River Basin Task Force, International Joint Commission.

Handbook of applied hydrology—a compendium of water-resources technology: In Chow, V.T. (ed.), New York, McGraw Hill, 1964.

Haeuber, R.A., and Michener, W.K., 1998, Issues in science and technology: p. 74–80.

Hollevoet, R., 1999, A comprehensive and multipurpose approach to watershed management—a concept, in Proceedings of the North Dakota Academy of Science flooding in North Dakota Symposium: v. 53.

Houston Engineering Inc., 1999, Hydrologic routing of the 1997 Red River flood: Study report for the Red River Watershed Management Board.

International Joint Commission, 1997, Red River flooding—short-term measures: Interim report of the International Red River Basin Task Force to the International Joint Commission, Ottawa–Washington, 65 p.

International Joint Commission, 2000, Living with the Red—a report to the governments of Canada and the United States on reducing flood impacts in the Red River Basin: 82 p.

Kingery, L.R.S., Frank, W.B., and Luther, M., 1999, Flood peak management using landscape storage in the Pembina River Basin, unpublished paper.

Korsching, P.F., Hoiberg, E.O., Bultena, G. L., and Padgitt, S.C., 2001, Soil erosion as a community issue—public perceptions at off-site impacts: Society and Natural Resources, v. 14, p. 67–76.

LeFever, J.A., Bluemle, J.P., and Waldkirch, R.P., 1999, Flooding in the Grand Forks–East Grand Forks–North Dakota and Minnesota Area: North Dakota Geological Survey Educational Series 25, 63 p.

Lykken, T.D., 2006, Towner County AG alert: NDSU Extension Service Issue 3, May 9, 2006, https://mylocalgov.com/TownerCountyND/WebSubsection.asp?key=319 (accessed May 2007).

Macek, R.K.M. 1997, Floods in the Red River of the North and Missouri River Basins in North Dakota and western Minnesota: U.S. Geological Survey Open-File Report 97-575, 8 p., http://nd.water.usgs.gov/pubs/ofr/ofr97575/index.html (accessed May 2007).

Mileti, D.S., Fitzpatrick, C., and Farhar, B.C., 1992, Fostering public preparations for natural hazards: Environment, v. 34, no. 3, p. 16–25.

Minnesota Department of Natural Resources, 2007, Red River Basin precipitation, www.dnr.state.mn.us/waters/groundwater_section/climatology/redriver.html (accessed May 2007).

Napier, T.L., McCarter, S.E., and McCarter, J.R., 1995, Willingness of Ohio landowner–operators to participate in a wetlands trading system: Journal of Soil and Water Conservation, v. 50, no. 6, p. 648–656.

National Research Council, 1999, New strategies for America's watersheds: Washington, D.C., National Academy Press: Washington, DC, 1999.

Natural Resources Conservation Service, 2007, www.nrcs.usda.gov/PROGRAMS/ (accessed February 2007).

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., and King, K.W., 2002a, Soil and Water Assessment Tool—theoretical documentation: Grassland, Soil and Water Research Laboratory, Texas Agricultural Experiment Station.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Srinivasan, R., and Williams, J.R., 2002b, Soil and Water Assessment Tool—user's manual: Grassland, Soil and Water Research Laboratory, Texas Agricultural Experiment Station.

Nortcliff, S., and Wong, M., 1995, Seasonal fluctuations of native available N and soil management implications: Nutrient Cycling in Agroecosystems, v. 42, no. 1–3, p. 13–26.

North Dakota State University Extension Service, 1999, Estimating crop yields: 1999 ProCrop Index, Fargo, North Dakota, North Dakota State University, www.ag.ndsu.nodak.edu/aginfo/procrop (accessed September 2004).

North Dakota State University Extension Service, Towner County AG Alert, Issue #3, May 9, 2006, Available at: https://mylocalgov.com/TownerCountyND/WebSubsection.asp?key=319 (Accessed June 2007).

Petrzelka, P., and Korsching, P., 1996, Journal of Environmental Education, v. 28, no. 1, p. 38–45.

Red River Basin Board, 2000, Drainage: Inventory Team Report.

Risk Management Agency, 2007, www.rma.usda.gov (accessed May 2007).

River Keepers, 2005, Red River Valley history, www.riverkeepers.org/pdf/history_of_red_river_valley.pdf (accessed February 2007).

Rogers, E.M., 1995, Diffusion of innovations (4th ed.): New York: Free Press.

Ryan, B., and Gross, N.C., 1943, The diffusion of hybrid seed corn in two Iowa communities: Rural Sociology, v. 8, p. 15.

St. George, S., and Rannie, B., 2003, The causes, progression and magnitude of the 1826 Red River flood in Manitoba: Canadian Water Resources Journal, v. 28, no. 1.

Sanocki, C., 2000, Using geographical information systems to identify potential water retention areas within the Wild Rice River Basin, northwestern Minnesota: U.S. Geological Survey draft document, 8 p.

Schroeder, J.W., and Goldman, D., 1990, Initial Evaluation of Create-A-Wetlands: Controlled Preplant Flooding on Spring Grains: Report for the North Dakota Wetlands Trust, Fargo, North Dakota, NDSU Extension Service.

Sheaffer, J.R., Mullan, D.J., and Hinch, N.B., 2002, Encouraging wise use of flood plains with market-based incentives: Environment, v. 44, no.1, p. 32–44.

Shutov, V.A., 2000, Snow cover in various relief and landscape conditions, in Water resources in extreme environments: American Water Resources Association, p. 19–24.

Socolofsky, S., Adams, E.E., and Entekhabi, D., 2001, Disaggration of daily rainfall for continuous watershed modeling: Journal of Hydrological Engineering, v. 6, no. 4, p. 300–309.

Solc, J., Eylands, K., Solc, J. Jr., Mueller, S., Engsrom, D., and Edlund, M., 2005, Subtask 7.2—reconstruction of paleohydrologic history of Devils Lake, North Dakota: Report for the U.S. Department of Energy Cooperative Agreement No: DE-FC26-98FT40320, Grand Forks, North Dakota, Energy & Environmental Research Center.

Spoor, C., 1992, Estimation of Grain Yields: North Dakota Wetlands Trust Create-a-Wetlands, 20 p.

Stoner, J.D., Lorenz, D.L., Wiche, G.J., and Goldstein, R.M., 1993, Red River of the North Basin, Minnesota, North Dakota, and South Dakota: Water Resource Bulletin, v. 29, no. 4, p. 575–615.

Todhunter, P.E., 2001, A hydroclimatological analysis of the Red River of the North snowmelt flood catastrophe of 1997: Journal of the American Water Resources Association, v. 37, no. 5, p. 1263–1278.

U.S. Army Corps of Engineers Hydrologic Engineering Center, 2001, HEC–RAS river analysis system user's manual.

U.S. Army Corps of Engineers and Federal Emergency Management Agency, 2003, Regional Red River flood assessment report—Wahpeton, North Dakota/Breckenridge, Minnesota to Emerson, Manitoba: St. Paul, Minnesota, U.S. Army Corps of Engineers.

University of Minnesota Extension, 2004, Soluble salts, www.extension.umn.edu/distribution/horticulture/components/173/-07.html (accessed May 2007).

Warkentin, A.A., 1999, Red River at Winnipeg hydrometeorological parameter generated floods for design purposes, in Proceedings of the Canadian Water Resources Association Winnipeg Conference—Red River flooding – decreasing our risks: Winnipeg, Manitoba, September.

Zandlo, J., Spoden, G., and Holz, A., 1997, Spring flooding of 1997—contributing climatic conditions, http://climate.umn.edu/doc/journal/flood_1997/snow97.htm#spring (accessed February 2007).

APPENDIX A

DATA SURVEY AND DATABASE CONSTRUCTION

DATA SURVEY AND DATABASE CONSTRUCTION

DATA SURVEY

The goal of the data survey was to identify the suitability, reliability, and accuracy of existing data and information needed to evaluate the feasibility of the Waffle® concept. As such, a major effort in the first year of this study was spent determining what data, studies, and models already exist for the Red River Basin (RRB) and, when necessary, collecting and compiling suitable data sources. Because the results of the data survey may be of interest and utility to other entities in the RRB, a database describing the type, location, source, and reliability of existing data was created and made available to the public on the EERC's Waffle Web site (www.undeerc.org/Waffle).

Tables A-1 and A-2 represent the nature of the data surveyed and, in some cases, acquired, during the course of this study. The data surveyed include models, infrastructure, topography, geology, hydrometeorology, imagery, and some software, as dictated by the needs of the project.

Models

Table A-1 represents the acquired hydrologic and hydraulic models assembled for use in this project to date. The model activities are discussed further in Section 2.4.

Infrastructure

While the landscape and environmental influences are fundamental to understanding the hydrologic dynamics of a basin, the infrastructure must be considered as a significant influencing factor governing the flow or lack of flow of surface waters throughout a watershed. The infrastructure referred to includes the transportation network of roads and railroads and the water-related structures supporting both urban and rural communities, such as culverts, bridges, ditches, drains, and other hydraulic structures (Table A-2). The key goal of this effort was to locate and, if feasible, collect and consolidate the infrastructural components of the RRB.

While infrastructural-type data do exist throughout the basin, there is no comprehensive database housing these data. The resources are dispersed among various entities and, therefore, support the need for information clearinghouses on water management such as the RRB Decision Information Network (RRBDIN). A comprehensive grasp of the RRB infrastructure cannot be gained without data from the federal, county, watershed district, water resource board, township and, in some cases, property owner levels. Since the majority of the U.S. portion of the RRB lies in Minnesota and North Dakota, the focus of the study efforts was on collection and/or documentation of infrastructural-type data from these two states.

Table A-1. Modeling Metadata

Description of Data	Extent of Coverage	Source
U.S. Army Corps of Engineers (USACE) UNET model Developed for the RRB in 1998 Calibrated using 1997 flood data, and verified using 1996 and 1979 flood data	Lake Traverse to Letellier, Manitoba	USACE
Wild Rice Floodplain Management Study WSP2 model and data Developed in February 1992	Wild Rice Floodplain	U.S. Department of Agriculture (USDA)
Flood hazard analyses for the Maple River in Cass and Ransom Counties Includes historical data the WSP2 model Published in July 1981	Cass and Ransom Counties, North Dakota	USDA
Red River One-Dimensional Unsteady Flow MIKE-11 Model Constructed for Red River over a distance of 280 km from Grand Forks, North Dakota, to Selkirk, Manitoba Calibrated using data from the 1997 flood, and verified using data from the 1996 flood	Selkirk, Manitoba, to Grand Forks, North Dakota	Klohn-Crippen Consultants Ltd. under contract to International Joint Commission
Over 200 Red River computer models Developed for various reaches within the RRB	U.S. RRB	USACE
Minnesota and Red River Corps Water Management System (CWMS) Watershed Modeling Study Includes hydrologic, water control, and hydraulic models	U.S. RRB and the Minnesota River Basin	Conducted by West Consultants, Inc., for USACE
Turtle River Floodplain Management Study Includes WSP2 models of the Turtle River	Grand Forks County, North Dakota	North Dakota State Water Commission
Regional Red River Flood Assessment Report Compilation of hydraulic models, flood profiles, and effective flow limits along the Red River	Wahpeton, North Dakota/Breckenridge, Minnesota, to Emerson, Manitoba	USACE
Red River of the North Main Stem Hydrologic Analysis Developed in 2001 Contains the Hydrologic Engineering Center (HEC-2) model Consists of various reaches along the main stem All are HEC-2 models extending from Wahpeton–Breckenridge to Emerson, Manitoba	Main stem U.S. RRB	USACE

Table A-2. Infrastructural Metadata

Description	Extent of Coverage	Source
Bridges, culverts (greater than 36 inches), and roads	Pembina County, North Dakota	Pembina County
Minnesota Department of Transportation (MNDOT) base map data of drainage ditches, municipal boundaries, railroads, national forests, state forests, national parks, state parks, military reservation lands, and indian reservation lands	Minnesota	MNDOT
MNDOT bridge, road, and culvert data	Minnesota	MNDOT
Incomplete inventory and inspection of Minnesota State and Interstate roads	Minnesota	MNDOT
Digitized cultural features of farmsteads, schools, cemeteries, and other cultural sites	Minnesota	EERC
Drainage and retention data drains, divisions, dugouts, dikes, and other structures	North Dakota	North Dakota State Water Commission
Critical facilities that have been identified in Pembina County	Pembina County, North Dakota	Pembina County
North Dakota Department of Transportation (NDDOT) bridge and culvert data	North Dakota	NDDOT
Scattered culvert data for Walsh, Grand Forks, and Traill Counties	Walsh County Grand Forks County Traill County	KLJ Engineering Office
Limited culvert data	Cass County	Cass County

Continued . . .

Table A-2. Infrastructural Metadata (continued)

Description	Extent of Coverage	Source
Culvert data, featuring direction of flow through the culvert, flow line elevation, natural ground elevation, and road or crossing elevation for low-lying areas.	Kittson County and some of Roseau County, Minnesota	Two Rivers Watershed District Office
Digital atlas and data for the inland waterways spill response mapping project, Red River mapping area; December 2001 This includes coverage for nonnavigational dams, pipelines, fixed oil storage facilities, railroads, major roads, water intakes, major water features, streams, marinas, managed resource areas, schools, special designated resource areas, tribal interests, hospitals, hazmat facilities (Tier II), boat accesses, historic sites, and archaeological sites.	Minnesota counties of Clay, Kittson, Marshall, Norman, Polk, and Wilkin and North Dakota counties of Cass, Grand Forks, Pembina, Richland, Traill, and Walsh	U.S. Geological Survey (USGS)
Bridges over 20 ft long and culverts over 5 ft in diameter	Steel County, North Dakota	Steel County, North Dakota

Roads

Because the premise of this study was based on temporary water storage on land surrounded by raised roads, high priority was placed on obtaining all available road elevation data, especially that in digital format.

However, after extensive survey of existing data, it was apparent that detailed road elevation data are limited throughout the RRB, especially for smaller county and township roads. The most extensive source of road data and information was the NDDOT and the MNDOT.

Minnesota Roads

The road data obtained from MNDOT comprise road centerlines within the state, which were digitized from USGS 7.5-minute quadrangles from 1990 to 1995 and last updated in January 2001. The road coverage incorporates U.S. and Minnesota trunk highways, county state aid highways, county and township roads, and municipal and unnamed streets. The map scale is 1:24,000, with a horizontal positional accuracy of ±40 ft (12 m). The coverage is complete for the Minnesota portion of the basin.

North Dakota Roads

NDDOT has compiled, maintained, and produced a collection of maps through digitizing and registering to the 1:24,000 USGS Public Land survey System (PLSS) data. The collection utilized global positioning system (GPS) equipment along highway centerlines. The coverage incorporates roads, rivers, and land use with varying source scales.

Regional Culvert Data

The culvert inventory obtained for Minnesota from MNDOT comprises over 2500 structures, including eight bridges crossing the Red River. The files contain the location, physical description, and dimensions of the individual structures. The original data were collected in the field using a GPS data logger with horizontal accuracy ranging from 0.5 to 5 meters, although generally speaking, the data are normally ±0.5–1 meter (Thomas Martin, personal communication, 2002). Similar resources were obtained from NDDOT comprising data from 3000 culverts and bridges, with an extensive inventory of structural and hydraulic components and features. The collection of culvert data obtained from MNDOT and NDDOT includes culverts that cross beneath highways and does not account for culverts under the jurisdiction of counties and townships.

Local Culvert Data

A limited number of counties and watershed districts have location information stored in digital format for the majority of their culverts; among them are Pembina County in North Dakota and Kittson County in Minnesota. These inventories were compiled by utilizing GPS to provide accurate positioning information which was then incorporated into a geographic information system (GIS). In these cases, only culverts greater than 36 inches in diameter and places where there are multiple culverts were documented. In addition, the culvert data sets vary among entities. For example, the Kittson County digital culvert inventory indicated the direction of flow through each culvert.

One factor that limits the widespread compilation of digital culvert inventories is the extensive resources needed to collect and/or digitize culvert data. For example, most of the culvert data from Water Resource Board and Watershed District offices is contained on paper in the form of culvert permits. Some of the older culverts may have no record filed. The reliability of the data also comes into question as a function of the date of data collection and the margin of error. Much of the existing culvert data, regardless of how the data are stored, are several decades old.

An assessment of the availability of culvert data at the county level, using Norman County, Minnesota, as an example, indicated that MNDOT houses the bulk of the digital culvert data, which consists of 188 culvert structures ranging in size from 2.5 to 10.4 ft (0.76 to 3.17 m) in diameter. All of these structures are along U.S. and Minnesota Trunk Highways. Several of the townships contacted within Norman County have no formal culvert inventory. County road construction plans have information pertaining to some of the newer culverts. The only other source of culvert information is through the watershed district's permit application submission process, available only in paper format. In 2003, the Minnesota Wild Rice Watershed Administrator, Mr. Jerry Bennett, estimated that there are perhaps 1000–2000 such permit applications (Jerry Bennett, personal communication, 2003).

While most entities at the county and township levels want to inventory the culverts in their jurisdiction, the funds are not readily available. As such, it is not uncommon for these entities to spread culvert inventory projects over time spans of 3–5 years. Others, such as the Barnes County Highway Department, focus their mapping projects on culverts with diameters greater than 48 inches. It is not unusual for such counties and watershed districts to inventory other specifically sized culverts at a given time, only to return when more funding is available to add a different size range of culverts.

In addition to government entities, another source of culvert data is the engineering firms within the basin. Because they are in the business of contracting and consultation, obtaining a free collection of their inventoried culverts is often difficult. Several of the most noted engineering firms that were contacted indicated that they had scattered data throughout counties but no comprehensive data set. In many cases, the data were prepared for their clientele; therefore, in order to release the data, the client would have to grant permission.

A questionnaire was developed and distributed to county engineers and watershed districts within the basin, the purpose of which was to assess 1) the extent and availability of georeferenced culvert data in the RRB and 2) the degree to which water boards and counties are using and plan to use GIS and GPS technologies to manage the information related to water conveyance structures in their jurisdictions. Of the 27 culvert-related questionnaires sent out to county engineers and watershed districts in the RRB, the EERC received 17 responses. Of the 17 returned, only four indicated that their jurisdiction has or maintains georeferenced culvert data. Two respondents indicated that all of their georeferenced data were electronic. The good news is that over half of the respondents are aware of plans to georeference culverts in their jurisdiction within the next 5 years.

Drains and Ditches

Information on regulated drainage and retention structures was obtained from the North Dakota State Water Commission's active database resources. These include records and data on drainage permits, dams, dikes, diversion structures, ponds, lagoons, and dugouts in North Dakota.

Data on Minnesota ditches were developed by MNDOT and completed in 2001. These data were digitized from USGS 7.5-minute quadrangles and include various types of ditches, as well as the transportation system, civil and political boundaries, and surface water features. The accuracy standards for 1:24,000-scale maps are on the order of ±40 ft (12.2 m) (U.S. Geological Survey, 1999).

Cultural Features

Also relevant to this study were the cultural features of the region, such as towns, military bases, homes, churches, schools, and state parks. Since flood mitigation studies are developed to protect communities and their way of life, it is important to minimize impacts to cultural features. The location of cultural features was taken into account during the evaluation of potential Waffle storage areas.

The cultural features for North Dakota were obtained from NDDOT. The coverage is from a GIS Base Map Data–Version 1.1a and was digitized from a source map of 1:126,720. The data set includes a description for state school lands, central business districts, cemeteries, beet dumps, and grain elevators, to name a few.

Data developed at a scale of 1:24,000 were obtained from MNDOT with coverages of municipal boundaries, state forests and parks, Indian reservation lands, and railroads (www.dot.state.mn.us/tda/basemap/index.html). As additional cultural features for Minnesota were not included in this data set but were needed to evaluate potential storage areas, the Energy & Environmental Research Center (EERC) digitized the location of homesteads, schools, and other cultural features. This effort was conducted using aerial photographs from the National Aerial Photography Program (NAPP) and from Terraserver, a Web site that contains free aerial photographs, topographic maps, and satellite imagery for the United States.

Hydrometeorologic Data

To better understand and model the hydrology of the RRB, data pertaining to the rate, duration, intensity, and spatial and temporal distribution of weather-related conditions were collected. Links to real-time station information, online data retrieval, and weather prediction models were collected for the U.S. portion of the RRB.

The meteorological data, obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (Table A-3), comprise daily observations from cooperative weather stations in the central United States and include air and soil temperatures, rainfall, snowfall, and evaporation elements. The period of record varies among stations but falls within the period from the 1850s through 2001.

Imagery

Imagery surveyed as part of this effort consisted primarily of aerial photography and, to a lesser degree, RADARSAT imagery (Table A-4).

Aerial Photographs

Aerial photographs of flooding along the Red River Valley during the 1997 flood were collected by Mr. Larry Ritzo of Ag Imaging. These aerial photographs comprise 19 CD-ROMs and include images of the flood and flooded towns throughout the valley during, or very near, the peak flood crest. The metadata indicate that the images were shot vertically from approximately 10,000 ft (3048 m) above sea level, using a 35-mm Nikon F camera from a Cessna 172 airplane with a camera hole cut in the floor. According to Mr. Ritzo, the goal was to follow the crest and photograph the river at or near its highest point. This project took nearly 3 weeks to complete (Larry Ritzo, personal communication, 2002).

RADARSAT Imagery

Six georeferenced RADARSAT images of the Red River Valley during the 1997 flood were obtained from USACE. RADARSAT imagery is particularly useful for detecting water and, therefore, is useful for flood monitoring and mapping www.space. gc.ca/asc/eng/satellites/ radarsat1/hydrology.asp). The images obtained were taken on April 10, 14, 20, 24, and 28 of 1997, with coverages extending from Horace to Halstad; Wahpeton–Breckenridge to Ada; 20 miles south of Wahpeton–Breckenridge to Fargo–Moorhead; Ada to north of Grand Forks; Shelly (Marsh River) to north of Oslo; and Oslo to Pembina–St. Vincent, respectively. The images are in black and white, with enhanced blue coloring to emphasize areas of severe flooding and ice jams.

Topographic Data

Topographic data available for the RRB are listed in Table A-5. Historically, USGS has been the primary source of topographic data; however, recent efforts to obtain higher-resolution data have resulted in the collection of elevation data using Light Detection and Ranging (Lidar).

USGS National Elevation Dataset (NED) Digital Elevation Model (DEM)

The only digital elevation data set available for the entire RRB is the USGS NED. At the onset of this project, the NED for the RRB was downloaded from the USGS Web site. NED is a raster product assembled and designed to provide national elevation data in a seamless form with

Table A-3. Hydrometeorologic Metadata

Description	Extent of Coverage	Source
Daily observations from cooperative weather stations, including air and soil temperature, rainfall, snowfall, and evaporation from the 1850s through 2001	Central United States	NOAA
Links to real-time station information, online data retrieval, and weather prediction modeling	U.S. RRB	Various sources

Table A-4. Imagery Metadata

Description	Extent of Coverage	Source
RADARSAT Images of the 1997 Flood	Main stem	USACE
Aerial photos used to track the crest of the flood along the river at or near its highest point, extending for some 3000 mi^2 (7770 km^2) along the main stem of the Red River	Main stem	Ag Imaging
Aerial photographs at a scale of 1:40,000 produced by NAPP	Minnesota	USGS

a consistent datum, elevation unit, and projection. Although some 10-meter resolution data are available, the entire RRB is represented by 30-meter resolution digital elevation data.

Light Detection and Ranging

Given the limited accuracy of existing DEMs, ±10 ft (3 m) under ideal conditions to an accuracy of ±30 ft (9 m), the advent of Lidar is a great boon to flood mitigation studies in the RRB (Fowler, 2001). In the Red River floodplains where small differences in elevation extend over several miles, Lidar can provide a high degree of enhanced accuracy. With a horizontal accuracy of 6–12 in. (15–30 cm) and a vertical accuracy of 6 in. (15 cm) or less, Lidar allows for collection of large areas of reliable elevation data. Coupled with the quick delivery of the data, Lidar is considered the least expensive method of obtaining detailed data over large areas (Fowler, 2001).

Table A-5. Topographic Metadata

Description	Extent of Coverage	Source
USGS DEM data coverage – a combination of the 7.5-minute series at 30- and 10-meter resolutions	U.S. RRB	USGS
Lidar Mosaics	Sheyenne River Corridor; Devils Lake, North Dakota; Pembina River, North Dakota; Wahpeton, North Dakota–Breckenridge, Minnesota; Fargo, North Dakota–Moorhead, Minnesota; Roseau, Minnesota; Warroad, Minnesota; and Wild Rice River, Minnesota	USACE
Lidar Mosaics	Fargo, North Dakota–Moorhead, Minnesota and Buffalo–Red Watershed	Houston Engineering

All of the existing publicly available Lidar-derived data for the RRB were obtained. This includes mosaics for the Sheyenne River Corridor; Devils Lake, North Dakota; Pembina River, North Dakota; Wahpeton, North Dakota–Breckenridge, Minnesota; and Fargo, North Dakota–Moorhead, Minnesota.

Recently, additional Lidar data have been made available through USACE; included are coverages for the following areas: Fargo, North Dakota, an extension (north) of the existing mosaic; Roseau, Minnesota; Warroad, Minnesota; and the Wild Rice River in Minnesota (Keith LeClaire, personal communication, 2003). In addition, Lidar data for part of the Buffalo–Red Watershed District was obtained from Houston Engineering, Inc.

The Lidar mosaics within the basin are governed by the priorities of Federal Emergency Management Agency (FEMA), the funding agency. Unfortunately, the Lidar data available for the RRB tend to be in locations along rivers that are typically flooded during major floods and would not be considered for Waffle-type storage scenarios.

Geologic Data

Soil data (Table A-6) were a critical component of the Soil and Water Assessment Tool (SWAT) models developed during the Waffle study. Soil data were also used to create a GIS layer of areas most suitable for water retention based on soil permeability.

A variety of entities manage and deliver soil information and data. Among them are the National Soil Information System (NASIS), the Soil Survey Geographic Database (SSURGO), the State Soil Geographic Database (STATSGO), the Laboratory Information Management

Table A-6. Geologic Metadata

Description	Extent of Coverage	Source
SSURGO Data Set	U.S. RRB	NRCS
STATSGO Data Set	U.S. RRB	NRCS
Soil Climate Analysis Network (SCAN) Site, a Source for Historic and Real-Time Soil Moisture and Pedon Data	Glacial Ridge, Polk County, Minnesota	NRCS

System (LIMS), the National Soil Geographic (NATSGO) database, and the Soil Survey Information System (SSIS). This is by no means a complete list. Many independent systems are used to deliver and manage these soil data and information; only a few are integrated. Therefore, the use of independent systems has resulted in spatial and attribute data having to be manually processed to bring data sets together. While there are continued efforts to improve integration of soil data and information into seamless coverage, presently, SSURGO and STATSGO are among the most widely used soil surveys. The following description of each of the above data sets was provided by the North Dakota State Natural Resources Conservation Service (NRCS) office. More detailed information can be found at www.ncgc.nrcs.usda.gov/ products/datasets.

NASIS integrates soil survey information, operations, and management and divides soil survey data into four major categories: 1) map unit records; 2) geographic area records; 3) point characteristics; and 4) standards, criteria, and guidelines. The system also includes ancillary tools, functions, and records to ensure the security, integrity, and utility of the soil survey data.

SSURGO is the most detailed geographic soil database, containing digital data developed from detailed soil survey maps that are generally at scales of 1:12,000, 1:15,840, 1:20,000, 1:24,000, or 1:31,680. The soil survey geographic database consists of spatial data from the digital soil survey map, attribute data from the soil survey area map unit record (data from NASIS), and associated source information (metadata).

The STATSGO geographic soil database is more general than the SSURGO database. It contains digital data developed at a uniform scale of 1:250,000 for the 48 conterminous states and Hawaii and Puerto Rico. It is very similar to the SSURGO database, but contains lower-resolution data.

The Soil Survey Laboratory (SSL) LIMS database contains point soil characterization data. It was developed to manage the NRCS soil databases.

The NATSGO database is used primarily for national and regional resource appraisal, planning, and monitoring. The boundaries of the major land resource areas (MLRAs) were used to form the NATSGO database. The MLRA boundaries were developed primarily from state general soil maps. Map unit composition for NATSGO was determined by sampling done as part of the 1982 National Resources Inventory. It is not being maintained and is not intended for watershed-level use.

Soil Moisture Data

Beyond achieving an understanding of land–atmosphere fluxes, studying soil moisture is crucial for understanding land–surface dynamics. These dynamics affect horizontal changes in moisture such as runoff, resulting in flooding when there is excess soil moisture and drought when there is a deficiency (Robock et al., 1997).

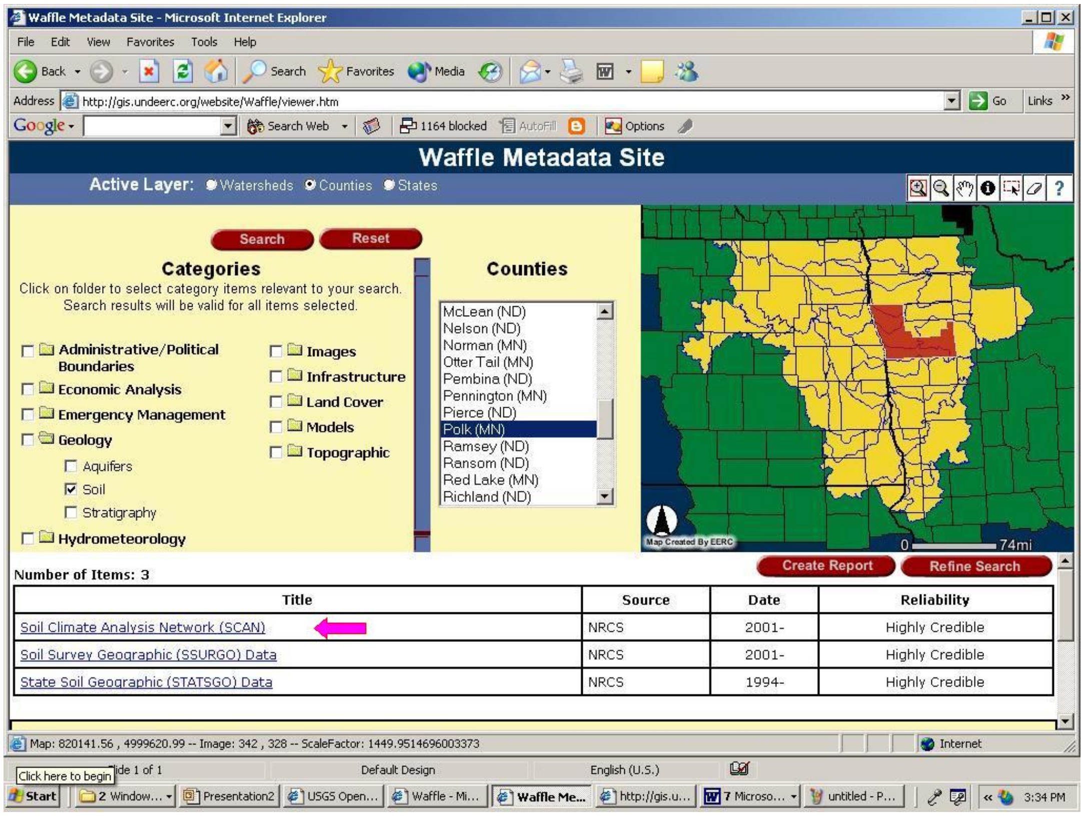
Through historic and real-time automated stations throughout the United States, soil moisture and pedon data are measured. One such location exists within the RRB, at the SCAN site for Glacial Ridge, Polk County, Minnesota. This site has been in existence since September 2001 (www.wcc.nrcs.usda.gov/scan/site.pl?sitenum=2050&state=mn). NRCS established this network to facilitate the assessment of resources and watershed determinations and provide an extensive, comprehensive soil–climate database throughout the United States. The soil moisture data are collected by a dielectric constant measuring device at several depths: 2 in. (5 cm), 4 in. (10 cm), 8 in. (20 cm), 20 in. (51 cm) and, occasionally, 40 in. (102 cm).

DATABASE CONSTRUCTION

After the data survey was completed, the EERC determined that the information compiled would be of interest to other entities involved in natural resource studies in the RRB. Therefore, an interactive, Web-based database was developed that contains information on the type, location, and reliability of data available for the RRB (Figure A-1). The database is available to the public through the Waffle Web site (www.undeerc.org/Waffle). Pertinent information regarding the data ownership, location, and documentation is provided and, if available, the data creation date, scale, and format.

Users can conduct data queries based on political boundaries, such as states or counties, or based on natural boundaries, like watersheds. In addition, queries can be conducted based on a specific data type, such as soil data, or topography. Alternatively, a user can search by title or publication year and be prompted by utilizing a series of drop-down selections. When a data set or resource of interest is found, additional detail is provided, including instructions on how to obtain the resource. Some of the resources are online for immediate transfer, while others need to be ordered.

A similar database was also constructed for the flood-related literature collected through this project. This interactive database is available to the public on the Waffle Web site and contains over 400 references that were compiled using Reference Manager. Users can search the contents of this database by author, keyword(s), and title. Query results include full reference citations and, whenever possible, publication abstracts. If the abstract of a publication was not available, an executive summary or introduction was cited as long as special copyright permission was granted by the publishers.



Active Layer: ○ Watersheds ● Counties ○ States

Click on folder to select category items relevant to your search. Search results will be valid for all items selected.

☐ Administrative/Political Boundaries
☐ Economic Analysis
☐ Emergency Management
☐ Geology
  ☐ Aquifers
  ☑ Soil
  ☐ Stratigraphy
☐ Hydrometeorology
☐ Images
☐ Infrastructure
☐ Land Cover
☐ Models
☐ Topographic

McLean (ND)
Nelson (ND)
Norman (MN)
Otter Tail (MN)
Pembina (ND)
Pennington (MN)
Pierce (ND)
Polk (MN)
Ramsey (ND)
Ransom (ND)
Red Lake (MN)
Richland (ND)

Number of Items: 3

Title	Source	Date	Reliability
Soil Climate Analysis Network (SCAN)	NRCS	2001-	Highly Credible
Soil Survey Geographic (SSURGO) Data	NRCS	2001-	Highly Credible
State Soil Geographic (STATSGO) Data	NRCS	1994-	Highly Credible

Figure A-1. Screenshot of Waffle Metadata Site showing a query conducted for soil data in Polk County.

REFERENCES

Fowler, R., 2001, Topographic Lidar, Chapter 7, in Maune, D.F., (ed.), Digital elevation model technologies and applications—the DEM users manual: Bethesda, Maryland, American Society for Photogrammetry and Remote Sensing, p. 207–236.

Robock, A., Vinnikov, Y.K., and Schlosser, A., 1997, Evaluation of land-surface parameterization schemes using observations: Journal of Climate, v. 10, p. 377–379.

U.S. Geological Survey, 1999, Fact Sheet FS-171-99, http://erg.usgs.gov/isb/pubs/Factsheets/Fs/7199.html (accessed May 2007).

APPENDIX B

IDENTIFICATION OF WAFFLE® STORAGE AREAS AND VOLUMES

IDENTIFICATION OF WAFFLE® STORAGE AREAS AND VOLUMES

INTRODUCTION

With nearly 36,000 square miles of the Red River Watershed to assess with regard to water storage potential, identifying storage areas suitable for the Waffle® concept was a challenge. After conducting a survey of existing data, the Energy & Environmental Research Center (EERC) determined that the most expedient method of identifying storage areas was to use a geographic information system (GIS) coupled with the best available digital data sets. The data sets identified for use in this effort include digital elevation models, the hydrologic network (rivers, streams, and lakes), cultural features, the transportation network (roads and railways), Public Land Survey System (PLSS) data, and satellite imagery.

The methodology used was based, in part, on a prior study conducted by the U.S. Geological Survey (USGS) to investigate the use of GIS to identify potential flood storage areas in the Wild Rice River Basin in Minnesota. The study used 1:24,000 digital basin boundaries, 1:100,000 USGS digital line graph (DLG) road data, and 1-arc-second (~30 meters)-resolution digital elevation model (DEM) data sets to identify storage areas. DEM grid cells intersecting roads identified by the DLG road data were artificially raised by 5 feet in order to simulate the roadbed. These altered DEM grid cells were used to detect sinks (i.e., those grids cells lower than the altered grid cells). Sinks contained by the raised roadways were identified from the grid and limited to those with surface areas larger than 10 acres and mean depths greater than or equal to 2.75 feet. Any potential storage areas located within Minnesota Department of Natural Resources protected-water boundaries were removed. The resulting storage volumes for the Wild Rice River Basin totaled 80,879 acre-ft (Sanocki, 2000).

METHODOLOGY

Similar to the USGS study for the Wild Rice River Basin, the Waffle project utilized GIS with DEMs to determine water storage potential for a watershed. However, a new approach was developed for estimating the volume of water that could be potentially stored behind raised roadways using the following GIS data layers:

1. USGS 1:24,000 digital topographic maps
2. USGS 1:24,000 digital orthophoto quadrangles (DOQ)
3. USGS 1-arc-second (~ 30 meters)-resolution National Elevation Dataset (NED)
4. USGS/Environmental Protection Agency (EPA) National Hydrology Dataset (NHD) compiled by Houston Engineering
5. PLSS data set for Minnesota and North Dakota

At the time of this study, these GIS data layers were the best freely available electronic data sets. The USGS 1:24,000 digital topographic maps are digital raster graphics (DRGs) created from scanned images of USGS topographic quadrangle maps (paper maps). The USGS DOQs are orthorectified aerial photographs that provide a snapshot of the Earth's surface. The NED is a raster data model of the terrain across the United States. The model provides elevation data in a seamless form with a consistent datum, elevation unit, and projection. Each cell in a NED grid stores the average elevation for the 30 by 30-meter area it encompasses. The NHD is a digital vector data set of water bodies and watercourses. The PLSS data set delineates sections that are the building blocks of the rectangular township and range system.

The storage volume for the Red River Basin (RRB) was calculated on a watershed-by-watershed basis. Such an approach was taken to allow for integration of the results with other watershed-modeling efforts being conducted in the project. Out of the 28 watersheds in the U.S. portion of the RRB, only 26 watersheds were considered for water storage (Figure B-1). The Devils Lake and Red Lake Watersheds were eliminated because of little or no drainage, or controlled drainage, into the Red River.

To conduct a basinwide assessment of storage areas, a set of criteria were used to eliminate areas that may not be suitable for water storage:

1. A section must not contain water bodies such as lakes, ponds, water treatment ponds, swamps, sloughs, and watercourses such as rivers and larger streams/creeks.

2. A section must not contain any of the following anthropogenic structures that would be submerged by water: towns, airports, landing fields, cemeteries, churches, farmsteads, and schools.

3. A section must be bounded by raised section roads, highways, or railroads.

4. Topographic maps must provide road survey points for a section.

In actuality, a section not meeting all of these criteria may sometimes still be suitable for water storage (i.e., a section contains a school, but it would not be affected by water storage). However, because of the large number of sections evaluated by this study, the project team decided to err on the conservative side rather than conduct a detailed evaluation of each potential storage area.

Both digital topographic maps and digital vector data sets of water bodies were used to identify whether or not a section contained lakes or ponds. Rivers and streams were recognized with the watercourse data set. Sections containing water bodies were removed from consideration because lakes and ponds naturally store water; hence, these sections have no need for Waffle storage. Large watercourses eliminated sections because of the cost and difficulties associated with their control.

Anthropogenic structures were identified by evaluating the digital topographic maps and DOQ data sets for a given section. The digital topographic maps, DOQs, and PLSS data sets were used to identify sections with roads that had the potential to contain water. Highways, interstates, and railroad tracks, all built on well-maintained, raised beds, are ideal as control structures for water. However, not all secondary roads would be suitable for water

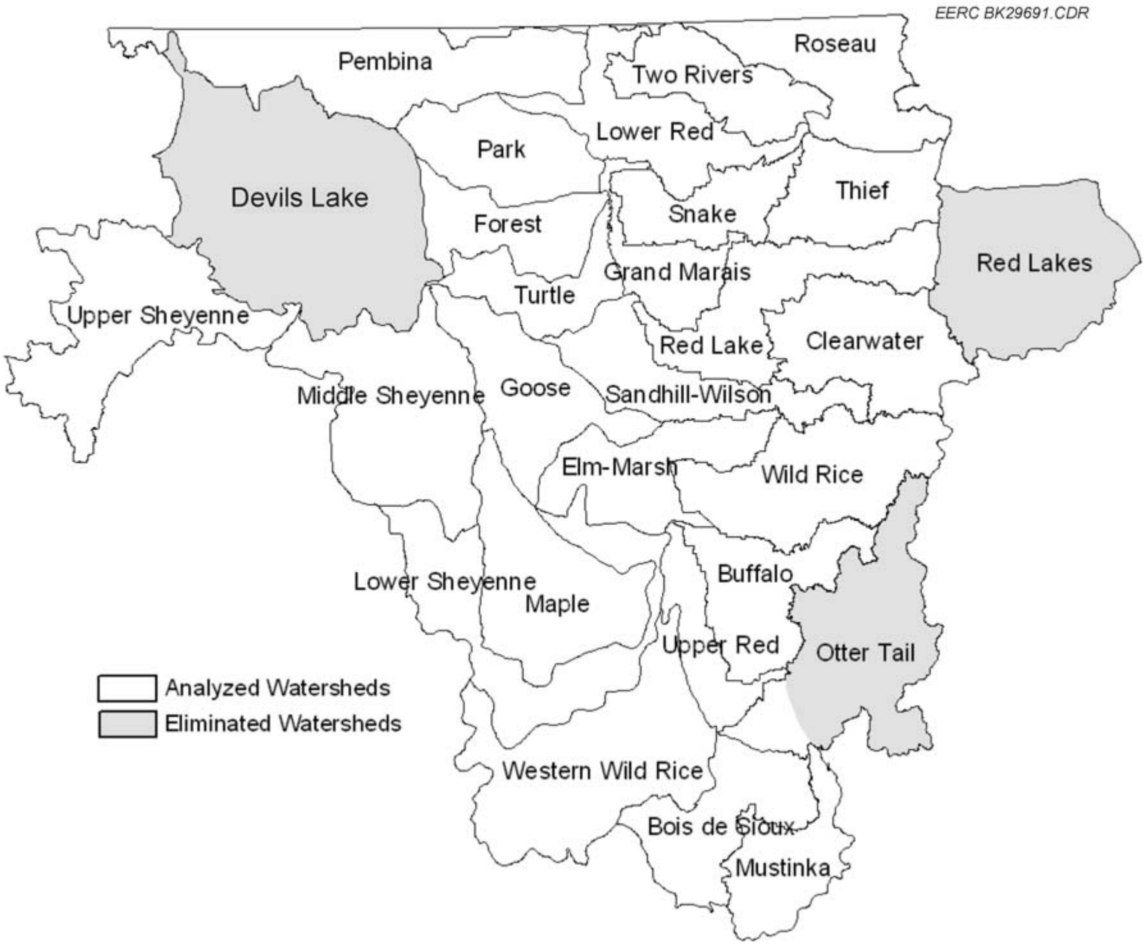


Figure B-1. Watersheds in the U.S. portion of the RRB.

retention. Only section roads were considered sufficient for storage purposes because nonsection roads may not be maintained or do not have raised roadbeds.

These criteria are fairly broad in definition and leave room for error. Unfortunately, the subjectiveness of this evaluation could not be eliminated. For example, some sections may only have sectional roads on two or three sides. The evaluator had to decide if the water could be contained using those roads. Figure B-2 gives an example of a section that has only two roads and is able to store water.

Road elevation data from topographic maps were used to estimate the volume of water that could be potentially stored by a section. Most sections had point elevations given in each corner and midway in between for a total of eight road elevations per section. In some cases, not all of these elevations were given, especially if section roads were not represented. If a road appeared to be in the topographically lowest part of the section and elevation data were not available, a determination was made to either estimate a road elevation or use the smallest of the available road point elevations. An ideal section would have no water bodies, watercourses, or cultural features, and it would be completely surrounded by raised roads with all eight elevation points.

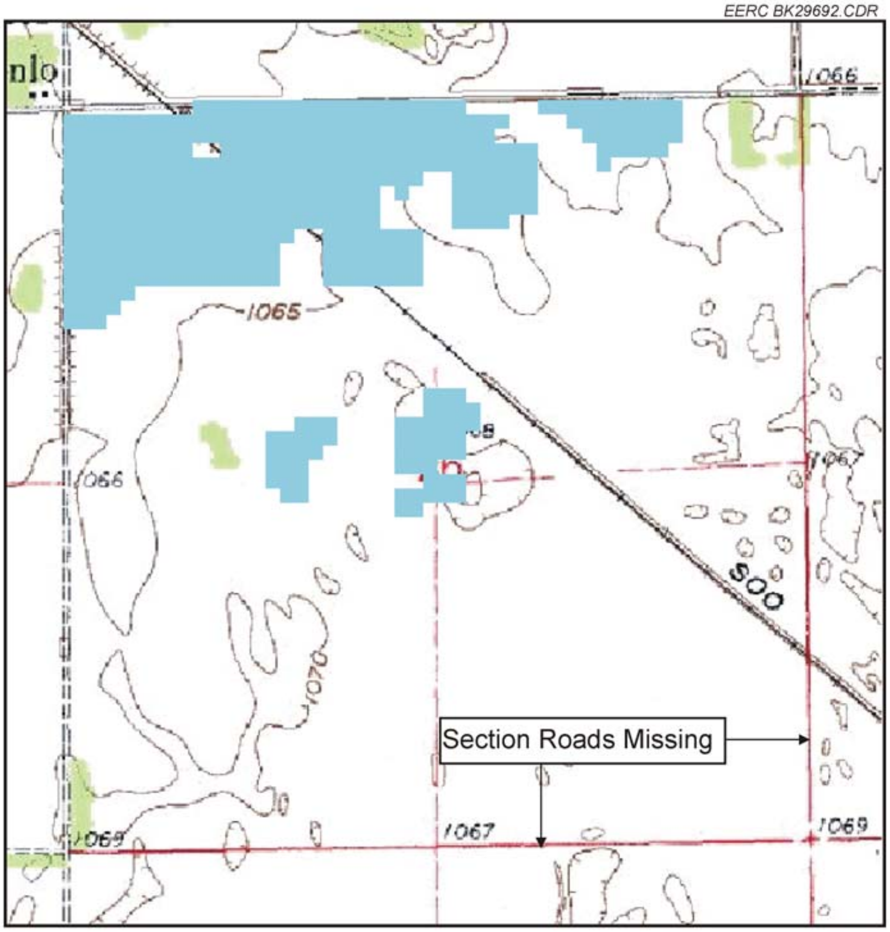


Figure B-2. An example of a PLSS section missing sectional roads on two sides, yet still potentially able to store water. Sink cells are shown in blue.

One caveat with this methodology is that it assumes that there are no road elevations lower than the eight points listed on the topographic map. Although this may not be the case, there were no other available sources of road elevation data, and it was infeasible to collect these data for the entire RRB. Figure B-3 shows an example on an ideal section.

Because it was unrealistic to calculate storage volumes for each individual section throughout the RRB, a statistical methodology was utilized to determine representative storage volumes for each watershed. This approach entailed the random selection of 20 sections within each RRB subwatershed for calculation of storage volumes.

To evaluate the potential storage volume for a given section, the lowest road elevation was determined from a digital topographic map. Elevations for NED grid cells within a section were compared to this minimum road elevation. Cells with lower elevations were considered as having the potential to store water. These cells are referred to as sinks. Figure B-4 shows an example

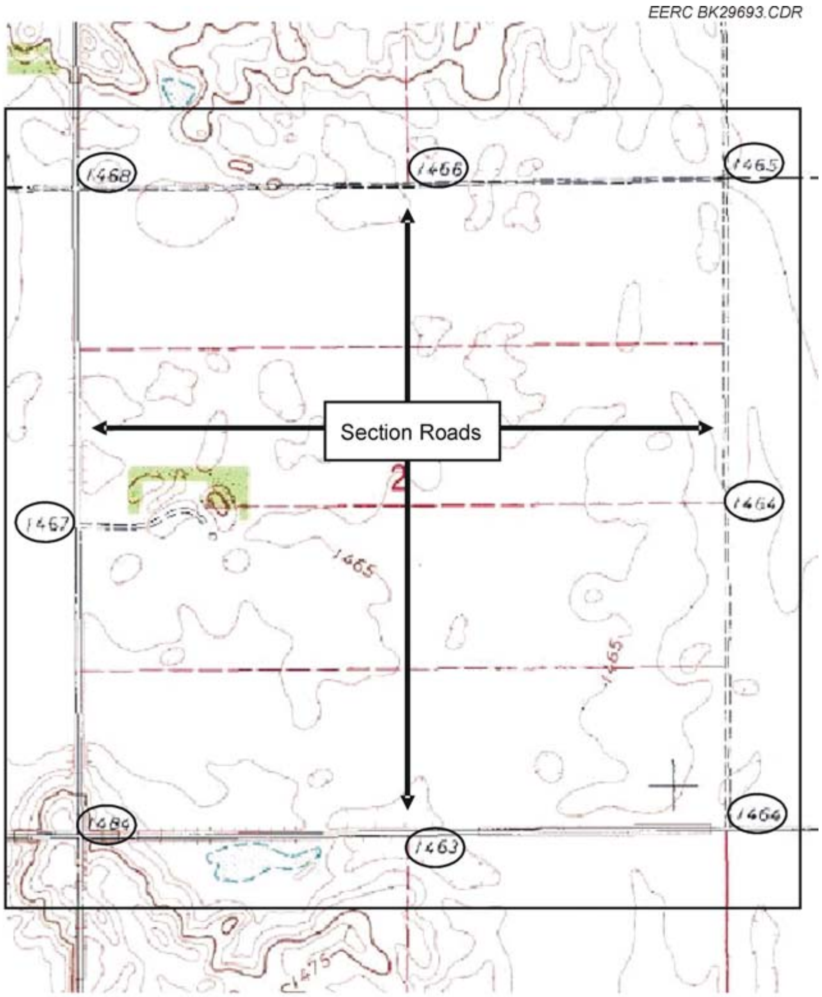


Figure B-3. Portion of a 1:24,000 topographic map illustrating an ideal section for storage analysis. Road elevations are circled.

of a calculated sink layer. The amount of water stored in each sink was calculated by determining the difference in elevation between the minimum road elevation and the sink's elevation. This difference was the theoretical depth of water stored above the area occupied by the grid cell. The storage volume for a section was determined by the collective amount of water held by sink cells within the section. More specifically, the depth of each sink was added together and multiplied by the area of a sink cell (i.e., 900 square meters). The resulting storage volume (in cubic meters) was then converted to acre-ft.

The statistical variability in storage volumes was then used to determine how many additional sections would have to be analyzed to come within 20% of the value if all sections in the watershed were evaluated. For example, the total number of sections within the Red Lake River Watershed is 1539; however, only 88 sections needed to be evaluated to come within 20% of the volume that would be determined using all sections. Any sections that were truncated (i.e., by boundaries) were eliminated from the storage volume calculations unless their area was

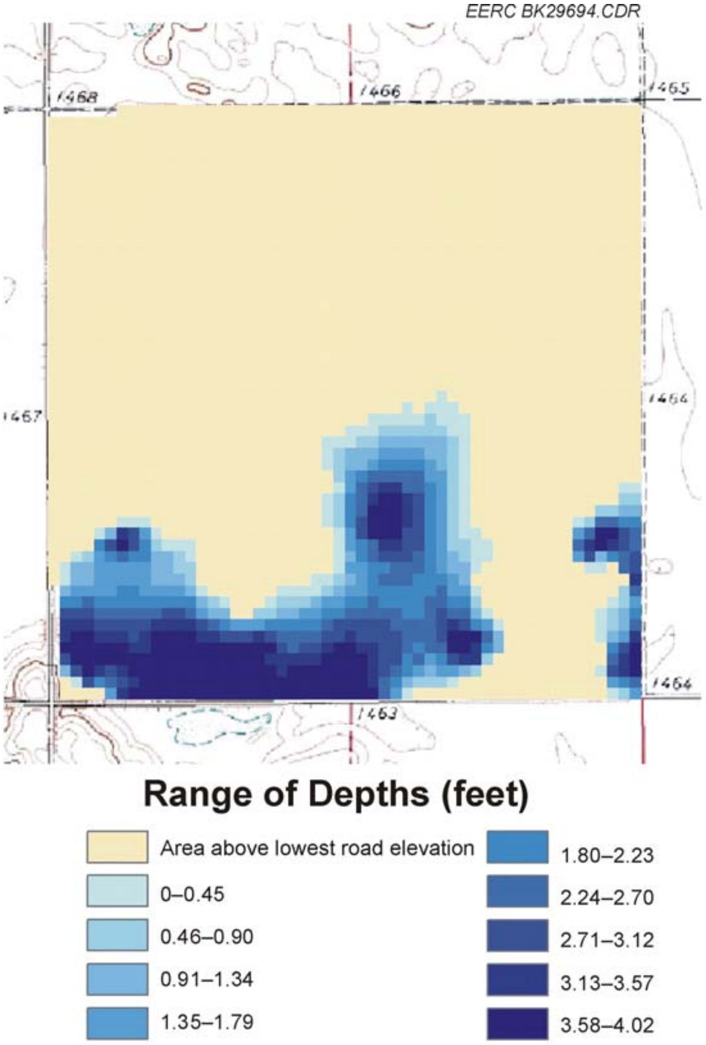


Figure B-4. An example of calculated sinks for a PLSS section. Depths are in feet.

greater than 0.75 miles. A total of 3732 individual sections throughout the RRB were ultimately analyzed using this approach. A breakdown of the number of sections analyzed per watershed is given in Table B-1.

To determine the approximate storage volumes of sections that were not explicitly analyzed in the above methodology, the average storage volumes of the analyzed sections were determined based upon relief categories. Relief was chosen as a means of categorizing storage volumes based on analysis of sample sections, which indicated an inverse relationship between storage volume and terrain relief. In general, the total storage potential decreases as the relief increases for a section. To better identify the relationship between relief and storage potential, each section with a volume greater than zero was plotted as a function of its elevation relief and

Table B-1. Number of Square-Mile Sections Evaluated per Watershed to Estimate Waffle Storage Volumes. A total of 3732 sections were evaluated throughout the RRB.

Watershed	Number of Sections Evaluated	Watershed	Number of Sections Evaluated
Bois de Sioux	121	Park	83
Buffalo	127	Pembina	134
Clearwater	154	Red Lake	88
Elm–Marsh	74	Roseau	312
Forest	256	Sandhill–Wilson	146
Goose	123	Snake	63
Grand Marais Creek	100	Thief	145
Lower Red	196	Turtle	101
Lower Sheyenne	100	Two Rivers	74
Maple	165	Upper Red	115
Middle Sheyenne	202	Upper Sheyenne	383
Mustinka	77	Western Wild Rice	119
Otter Tail	170	Wild Rice	104

corresponding potential storage volume. Figure B-5 is a graph of the plotted sections that illustrates the inverse relationship between storage potential and relief. A cumulative distribution of storage based on relief was created to determine if readily identifiable relief categories existed as a function of storage. Figure B-6 illustrates this distribution. Four relief categories were identified from the distribution: 0 to 2, 2 to 4, 4 to 10, and 10 to 100 plus meters. These categories were chosen based on significant changes in slope of the curve, which indicates the rate of change of storage with relief.

Once each of the sample sections in a watershed were evaluated, the total watershed volume was calculated using the average volume of the sample sections. The PLSS data set was used to find the number of sections in the watershed having an area of 0.75 square miles or greater. This number was multiplied by the average volume. To account for the sections that were less than 0.75 square miles, the area of these sections was added together and rounded to a whole number. This whole number was then multiplied by the average volume to obtain an estimate of the storage volume in those sections less than 0.75 square miles. The total estimated storage volumes using these two techniques were added together to determine the total potential water storage volume for the entire watershed.

INITIAL STORAGE ESTIMATES

Storage Estimation for Each Watershed

All 26 of the aforementioned RRB watersheds were evaluated through the methodology described in Section 2. Table B-2 shows the results found for each watershed. The storage values were rounded based on a 20% RSD (relative standard deviation). Hence, for a watershed with at least 50,000 acre-ft of water storage, the estimated storage value is accurate to the nearest 10,000 acre-ft, while those watersheds with smaller storage estimates are accurate to the nearest 1000 acre-ft.

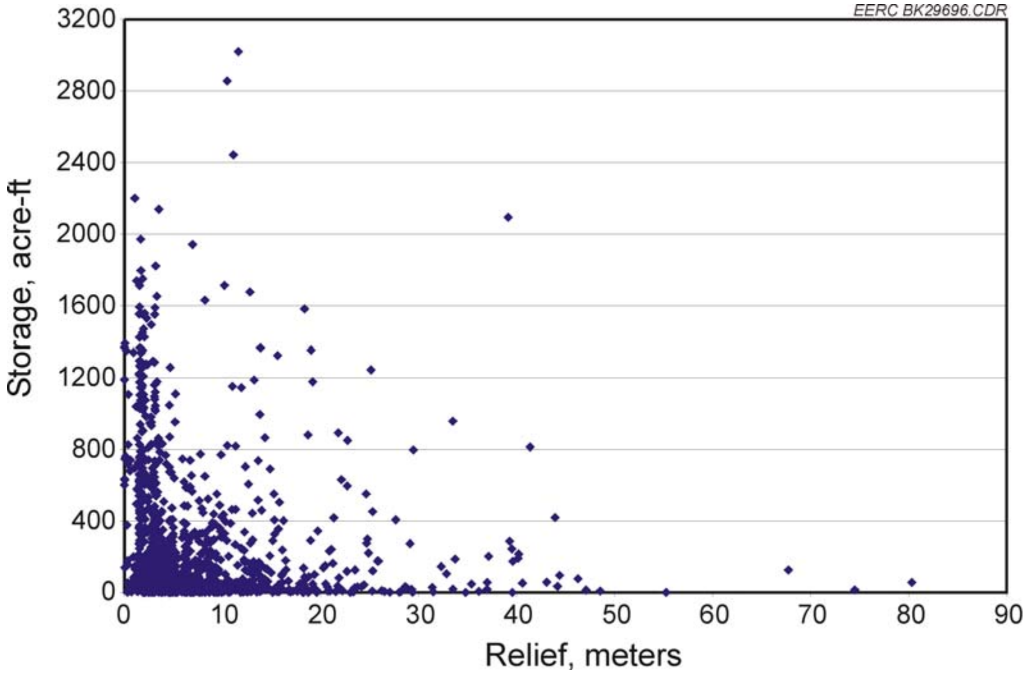


Figure B-5. Relief plotted against potential storage for 1220 sections.

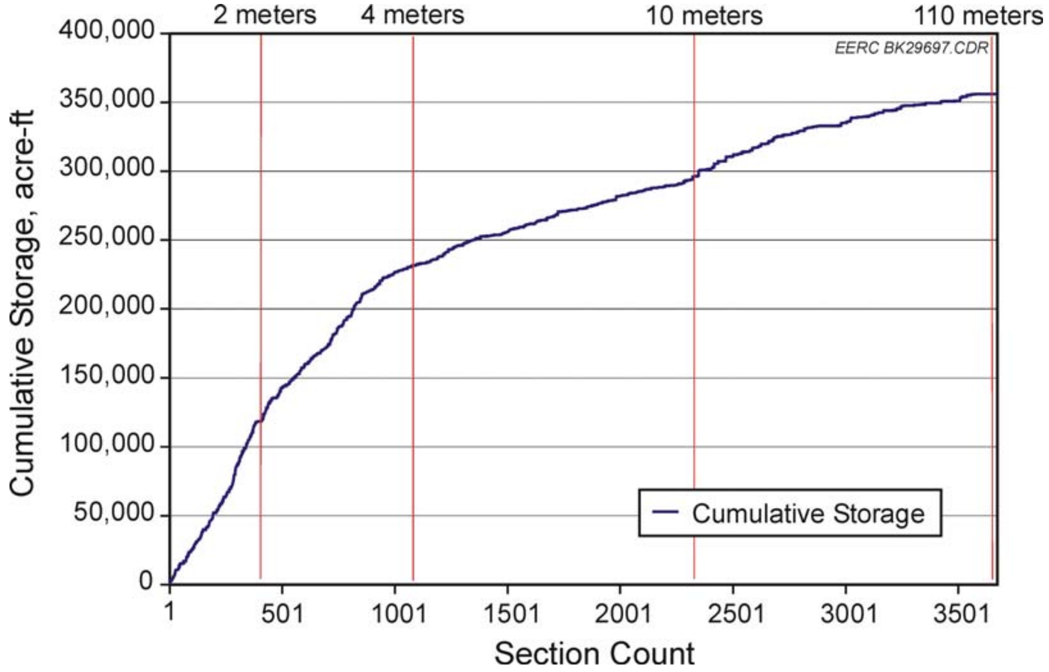


Figure B-6. Cumulative distribution graph for potential storage with over 3700 sections evaluated for the RRB. Vertical lines indicate category breaks in relief.

Table B-2. Initial Estimates of Waffle Storage for Watersheds in the RRB (estimates do not account for freeboard, natural storage, or the 1997 floodplain)

	Watershed Name	Sample Size	Mean Storage per Section, acre-ft	No. of Sections >0.75 sq. mile	Area of Sections <0.75 sq. mile	Estimated Storage Volume, acre-ft	% of Total Estimated Storage, %	±20% RSD, acre-ft	Lower Limit Storage Volume, acre-ft	Upper Limit Storage Volume, acre-ft
1	Bois de Sioux	121	97	1043	73	108,000	3.3	22,000	86,000	130,000
2	Buffalo	127	79	1059	62	89,000	2.7	18,000	71,000	107,000
3	Clearwater	154	46	1335	53	64,000	1.9	13,000	51,000	77,000
4	Elm–Marsh	74	297	1072	54	334,000	10.1	67,000	267,000	401,000
5	Forest	256	70	838	47	63,000	1.9	13,000	50,000	76,000
6	Goose	123	86	1216	53	109,000	3.3	22,000	87,000	131,000
7	Grand Marais Creek	100	267	572	53	167,000	5.1	33,000	134,000	200,000
8	Lower Red	196	209	1069	89	222,000	6.7	44,000	178,000	266,000
9	Lower Sheyenne	100	205	1579	110	344,000	10.4	69,000	275,000	413,000
10	Maple	165	95	1548	59	152,000	4.6	30,000	122,000	182,000
11	Middle Sheyenne	202	49	1972	69	99,000	3.0	20,000	79,000	119,000
12	Mustinka	77	46	814	42	39,000	1.2	7800	31,200	46,800
13	Otter Tail	170	85	238	70	9000	0.3	1800	7200	10,800
14	Park	83	134	1029	42	143,000	4.3	29,000	114,000	172,000
15	Pembina	134	73	1942	98	149,000	4.5	30,000	119,000	179,000
16	Red Lake	88	94	1265	64	124,000	3.8	25,000	99,000	149,000
17	Roseau	312	81	1192	39	99,000	3.0	20,000	79,000	119,000
18	Sandhill–Wilson	146	124	1046	68	139,000	4.2	28,000	111,000	167,000
19	Snake	63	70	741	42	55,000	1.7	11,000	44,000	66,000
20	Thief	145	97	994	42	100,000	3.0	20,000	80,000	120,000
21	Turtle	101	97	658	51	69,000	2.1	14,000	55,000	83,000
22	Two Rivers	74	91	913	43	87,000	2.6	17,000	70,000	104,000
23	Upper Red	115	199	561	41	120,000	3.6	24,000	96,000	144,000
24	Upper Sheyenne	383	45	1851	93	88,000	2.7	18,000	70,000	106,000
25	Western Wild Rice	119	91	2218	94	210,000	6.4	42,000	168,000	252,000
26	Wild Rice	104	71	1573	61	114,000	3.5	23,000	91,000	137,000
	Totals	3732		30,338	1612	3,296,000	100.00		2,634,400	3,957,600

Table B-1 also illustrates the variability of estimated storage volumes between the watersheds. The Lower Sheyenne and Elm–Marsh Watersheds have significantly larger storage potential than the others. These two watersheds contain roughly 20% of the RRB's estimated total storage. Both watersheds have large standard deviation and mean values of potential storage per section, which suggests that these watersheds have sections with enormous storage potentials.

Both the Western Wild Rice and Lower Red River Watersheds have an estimated storage potential that is approximately 6.5% of the total for the RRB. Although the amount of storage is similar between the watersheds, the Lower Red River Watershed has fewer sections within its boundaries, thus a larger mean value of storage per section. In short, sections within the Lower Red River Watershed have a higher potential to store larger volumes of water than sections within the Western Wild Rice Watershed.

STORAGE ADJUSTMENTS

Freeboard Versus No Freeboard

The Waffle storage volumes determined by the above approach are considered the maximum potential storage, assuming no roads are raised. In practice, Waffle storage areas would likely include freeboard between the stored water surface and the lowest point on the surrounding roads. In addition, the maximum storage volume estimates include natural storage, or the water that does not contribute to downstream flooding because it remains trapped in small pools on the landscape which do not drain. To gain a better estimate of Waffle storage volumes, the original storage estimates were reduced to account for freeboard and natural storage.

To determine an appropriate volume reduction to account for freeboard, four subwatersheds were selected for comparison purposes, including the Forest River, Lower Sheyenne River, Red Lake River, and Wild Rice River (Minnesota) subwatersheds. These four subwatersheds were selected because they encompassed the range of physical characteristics (size, shape, topographic variation, land use/land cover, and distribution of waterways and lakes) exhibited by the subwatersheds of the RRB. The same technique used to calculate the original storage volume estimates was applied to these subwatersheds, except that the lowest road elevation was further reduced by 1 foot to account for 1 foot of freeboard. Table B-3 compares the results between the freeboard and no-freeboard scenarios.

Three of the four watersheds had a reduction in storage of 42%–45% as a result of including a 1-foot freeboard. The fourth watershed, the Lower Sheyenne, had a storage reduction of only 23%. A statistical test (t-test) was performed on the freeboard results from all four watersheds for comparison with the remaining watersheds in the RRB. It was determined that a 15% to 65% reduction was necessary in the remaining watersheds to account for freeboard within a 90% confidence interval. Based on this information, it was decided that two methods would be used to account for freeboard. One method used a conservative approach and reduced storage volumes by 50% to account for freeboard. The other method used a less conservative (herein referred to as moderate) approach and reduced storage volumes by 25% to account for

Table B-3. Estimated Storage Volumes Compared Between 1-foot Freeboard and No-Freeboard Scenarios for the Forest River Watershed*

	Red Lake		Lower Sheyenne		Wild Rice		Forest	
Watershed	Without Freeboard	1-foot Freeboard	Without Freeboard	1-foot Freeboard	Without Freeboard	1-foot Freeboard	Without Freeboard	1-foot Freeboard
Sample Size, no.	88	126	100	114	104	108	256	304
Mean, acre-ft	94	51	205	157	71	41	70	37
SD, acre-ft	246	141	491	424	235	152	209	122
CV	0.38	0.36	0.42	0.37	0.30	0.27	0.33	0.30

* SD = standard deviation; CV = coefficient of variation = mean/SD.

freeboard. These percentages were within 5% of the range exhibited by the test watersheds and, therefore, were deemed representative.

In actuality, in many cases, the lowest point along the roads surrounding a storage section may occur along a small section of road that would be worth raising to obtain a significant increase in storage volume. For example, as illustrated in Figure B-3, there is only one lowest elevation value of 1463. If that low point occurred only along a short distance of road, it may be worth building the road up to an elevation of 1464 to obtain a significant increase in storage volume.

Additional Storage Adjustments

Two additional adjustments were made to the freeboard storage calculations to provide a better estimate of Waffle storage. The first adjustment was for natural storage. Although the methodology excluded storage attributed to permanent water bodies and watercourses such as lakes, dams, and rivers, natural storage associated with shallow depressions was included in the volume estimates. Shallow depressions of varying size and depth are present on practically all surfaces. For example, many fields in the region contain shallow depressions that will store water and only drain by evaporation and/or infiltration. Thus some degree of storage already exists on the landscape, regardless of whether or not water is retained by Waffle storage. To account for this natural storage, Waffle storage estimates were reduced accordingly.

Based on values listed in the literature, measurements of natural or depression storage range from a ¼- to ½-inch depth of water for pervious surfaces with gentle to moderate slopes (Handbook of Applied Hydrology, 1964). Over an entire section, the volume occupied by a half inch of water is approximately 25 acre-ft and 12.5 acre-ft for a quarter inch of storage. Therefore, a conservative approach and a less conservative approach were taken to adjust for natural storage. For each watershed, both 25 acre-ft and 12.5 acre-ft were multiplied by the number of whole sections (≥ 0.75 square miles) and subtracted from the freeboard estimate of storage. The conservative reduction of 25 acre-ft per section was subtracted from the conservative freeboard estimate (50% reduction). The less conservative 12.5-acre-ft estimate of natural storage was subtracted from the moderate freeboard estimate (25% reduction). In reality, since many of today's fields have been laser-leveled and many of the naturally occurring depressions have been filled or drained, natural storage estimates may be closer to the lower estimate or, possibly, even lower.

One final adjustment was made to the storage volume estimates – the removal of PLSS sections within the 1997 floodplain. Unlike the previous storage adjustments, this one was applied only to the conservative storage volume estimates. The assumption was that in spring seasons with extreme runoff, areas within this floodplain may be flooded or only available for storage toward the end of flooding events. Ideally, if upstream storage were implemented, many of the areas within this floodplain would then be available for storage; however, in keeping with a very conservative approach to estimating storage, all areas within the 1997 floodplain were eliminated from consideration. The U.S. Army Corp of Engineers (USACE) provided GIS files outlining the floodplain as depicted on satellite imagery during the 1997 flood. The elimination of storage sections within the 1997 floodplain significantly reduced the estimated storage potential of some watersheds since these areas tend to be flat and have a high potential for storage.

The original storage volume estimates and adjusted estimates using conservative and moderate assumptions are listed in Table B-4 and shown in Figure B-7. The most conservative Waffle storage volume estimate for the RRB, and that explicitly modeled in this study, including volume reductions to account for freeboard, natural storage, and areas located in the 1997 floodplain, is approximately 583,400 acre-ft. The moderate storage volume estimate for the RRB is 2,188,400 acre-ft. The original total storage volume estimate is 3,296,000 acre-ft.

As shown in Table B-3 and Figure B-5, the reduction of storage volumes to account for freeboard and natural storage, as well as areas located in the 1997 floodplain, had a dramatic reduction in storage volumes compared to initial estimates. The initial estimates indicated that more than half of the watersheds had potential storage capacities of 100,000 or more acre-ft of water, while most of the adjusted storage capacities had less than 100,000 acre-ft. The conservative Waffle storage estimate for the RRB (583,400 acre-ft) is almost one-sixth of the initial estimate of 3,296,000 acre-ft.

As a comparison, USGS estimates of the water storage potential in the Wild Rice River Watershed (of Minnesota) were 80,879 acre-ft (Sanocki, 2000). The original storage estimate, without accounting for freeboard, natural storage, or the 1997 floodplain, was 120,000 acre-ft. The adjusted estimates using the most conservative and moderate adjustments were 15,600 and 71,000, respectively. The moderate storage estimate was very close to the USGS estimate; however, additional comparisons would be needed to make conclusions regarding the accuracy of either approach. This indicates that the conservative storage estimates may considerably underestimate storage potential.

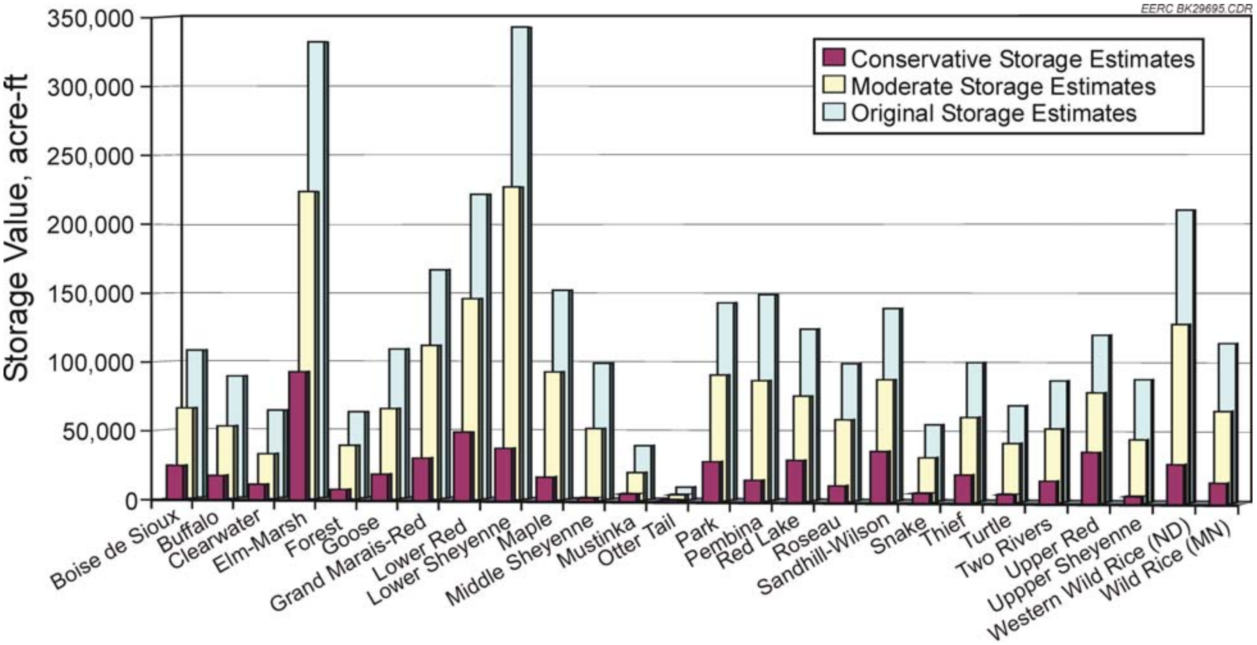
Table B-4. Original and Adjusted Storage Volume Estimates. The original values were not adjusted to account for freeboard, natural storage, or the 1997 floodplain. The moderate storage estimates included a 25% volume reduction to account for freeboard and a 12.5-acre-ft reduction per section to account for natural storage. The highly conservative storage estimates include a 50% volume reduction to account for freeboard, a 25-acre-ft reduction per section to account for natural storage, and elimination of all storage areas in the 1997 floodplain.

Watersheds	USGS 8-Digit HUC	Storage Estimate No Adjustments, acre-ft	Moderate Storage Estimate, acre-ft	Highly Conservative Storage Estimate, acre-ft
Bois de Sioux	09020101	108,000	71,100	24,900
Buffalo	09020106	89,000	56,700	17,600
Clearwater	09020305	64,000	35,200	11,400
Elm–Marsh	09020107	334,000	240,500	93,100
Forest	09020308	63,000	39,100	8000
Goose	09020109	109,000	70,700	19,100
Grand Marais–Red	09020306	167,000	119,700	30,900
Lower Red	09020311	222,000	156,800	49,700
Lower Sheyenne	09020204	344,000	243,000	38,200
Maple	09020205	152,000	99,800	17,500
Middle Sheyenne	09020203	99,000	56,100	2700
Mustinka	09020102	39,000	21,800	5700
Otter Tail*	09020103	9000	4800	1600
Park	09020310	143,000	97,600	29,200
Pembina	09020313	149,000	93,500	16,100
Red Lake	09020303	124,000	81,500	30,400
Roseau	09020314	99,000	63,400	12,400
Sandhill–Wilson	09020301	139,000	94,100	37,100
Snake	09020309	55,000	34,000	7300
Thief	09020304	100,000	65,800	20,500
Turtle	09020307	69,000	45,400	6700
Two Rivers	09020312	87,000	56,800	16,400
Upper Red	09020104	120,000	84,400	37,000
Upper Sheyenne	09020202	88,000	48,600	5700
Western Wild Rice (North Dakota)	09020105	210,000	137,000	28,600
Wild Rice (Minnesota)	09020108	114,000	71,000	15,600
	Total Storage:	**3,296,000**	**2,188,400**	**583,400**

* Only a small portion of the Otter Tail Watershed was evaluated for Waffle storage (see Figure B-1).

DISTRIBUTION OF STORAGE

A key goal of the Waffle project was to determine the reduction in RRB tributary flow as a result of Waffle storage. The Soil and Water Assessment Tool (SWAT) was the hydrologic model chosen to accomplish this goal (see Section 2.4 for further details). In order to evaluate the effects of Waffle storage, the SWAT model required the location and volume of individual Waffle storage parcels. Water storage was initially calculated on a watershed-by-watershed basis, and although this provides information about storage volumes, more specific information



B-7. Comparison of Waffle storage estimates.

about storage distribution was necessary for the SWAT model. As a result, storage had to be distributed among PLSS sections within the basin.

It was decided that the most conservative storage volume estimates would be explicitly modeled using SWAT. As such, the distribution of storage back to the landscape was applied using only the lowest storage volume estimate (583,400 acre-ft).

The even distribution of water among all sections was determined to be unrealistic since many sections were inappropriate for water storage (i.e., if they contained a cultural feature) and sections with less topographic relief are more likely to store water. Hence, PLSS sections located in urban areas and within the 1997 floodplain were removed from consideration. Sections with large water bodies or significant watercourses such as rivers were also eliminated from the distribution. The remaining sections were deemed potential candidates for water storage.

The further distribution of water was based on the relief categories previously discussed. Each category was assigned a value reflecting the probability that sections in that category would have adequate storage potential. A high probability of 95% was assigned to the 0–2-meter relief category; a moderate probability of 75% to the 2–4, and a low probability of 25% for the 4–10-meter category. Zero probability was assigned to the 10- to 100-meter-plus category because it was judged to have a very poor potential for efficient water retention. The probabilities were chosen subjectively because of the lack of information available on land suitability.

Total storage potential estimated for each watershed included contributions from sections in the 10–100-meter-plus category. A conflict arises because the distribution of water is limited to sections from the three smallest relief categories. In order to prevent the distribution of water associated with the 10–100-meter-plus category to the other three categories, storage potential for this category was subtracted from a watershed's total storage potential.

The distribution of water storage was limited to those sections with areas greater than or equal to 0.75 square miles. Smaller sections were left out because the chosen method for distributing the storage does not account for size of section. Consequently, the estimated storage potential for a watershed was adjusted to not include contributions from these "partial" sections.

The adjusted water storage volumes were divided by the number of sections in the three lowest-relief categories to determine the average storage per section for a watershed. In order to assign a unique storage value to each category, the average storage per section was multiplied by a weight function. The following equation provides an example of the calculation for the 0- to 2-meter relief category:

$$\frac{95\% \times (A + B + C)}{95\% \times A + 75\% \times B + 25\% \times C} \times \frac{\begin{array}{c}\text{(Total Volume Less}\\ \text{Very Poor Category)}\end{array}}{(A + B + C)} = \begin{array}{c}\text{Average Storage}\\ \text{per Section}\end{array} \qquad \text{[Eq. 1]}$$

A, B, and C represent the number of sections that fall in the 95%, 75%, and 25% probability categories, respectively. The term on the left represents the weight function. The above equation can be simplified to the following:

$$\frac{95\%}{95\% \times A + 75\% \times B + 25\% \times C} \times \begin{array}{c}\text{(Total Volume Less}\\ \text{Very Poor Category)}\end{array} = \begin{array}{c}\text{Average Storage}\\ \text{per Section}\end{array} \qquad \text{[Eq. 2]}$$

In Equation 2, the first term on the left-hand side was referred to as the geographical distribution factor for the 0- to 2-meter-relief category. The geographical distribution factor takes into account the number of sections and storage probabilities for each relief category. The right-hand term represents the estimated storage potential for a watershed minus the storage potential from the 10- to 100-meter-relief category and sections smaller than 0.75 square miles as previously mentioned. Small sections were removed from consideration, because the chosen distribution method does not account for section size. Instead, the method assumes all sections to be approximately 1 square mile.

Geographical distribution factors were calculated for the three lowest-relief categories for each watershed. The application of these factors in Equation 2 resulted in the calculation of storage volumes for each of the three relief categories for every watershed. The breakdown of storage according to relief category for each watershed is shown in Table B-4. Again, the distribution of storage was only applied to the most conservative storage estimates.

In summary, storage potential for each watershed was adjusted to exclude storage from partial sections (less than 0.75 square miles) and sections with terrain relief equal to or greater than 10 meters. Three geographical distribution factors were applied to the adjusted storage potential for each watershed, which resulted in storage estimates for the three lowest-relief

Table B-4. Breakdown of Storage

	Watersheds	Relief, m	Average Storage Volume per Section, acre-ft	Average Storage Volume for All Sections, acre-ft
1	Bois de Sioux	0–2 m	107.7	9800
		2–4 m	79.7	12,400
		4–10 m	9.9	2700
				Total: 24,900
2	Buffalo	0–2 m	124.3	6800
		2–4 m	92.9	8900
		4–10 m	14.3	1900
				Total: 17,600
3	Clearwater	0–2 m	51.9	4600
		2–4 m	35.7	6800
		4–10 m	0.0	0
				Total: 11,400
4	Elm–Marsh	0–2 m	277.6	38,900
		2–4 m	213.9	40,000
		4–10 m	54.6	14,200
				Total: 93,100
5	Forest	0–2 m	84.4	2400
		2–4 m	61.4	4800
		4–10 m	3.8	800
				Total: 8000
6	Goose	0–2 m	126.5	4700
		2–4 m	94.6	9200
		4–10 m	14.9	5200
				Total: 19,100
7	Grand Marais Creek	0–2 m	181.4	10,900
		2–4 m	137.9	16,400
		4–10 m	29.3	3600
				Total: 30,900
8	Lower Red	0–2 m	144.1	16,000
		2–4 m	108.2	27,000
		4–10 m	19.4	6700
				Total: 49,700
9	Lower Sheyenne	0–2 m	217.8	7600
		2–4 m	166.7	15,300
		4–10 m	38.9	15,300
				Total: 38,200

Continued . . .

Table B-4. Breakdown of Storage (continued)

	Watershed	Relief, m	Average Storage Volume per Section, acre-ft	Average Storage Volume for all Sections, acre-ft
10	Maple	0–2 m	108.8	3400
		2–4 m	80.6	9400
		4–10 m	10.2	4700
				Total: 17,500
11	Middle Sheyenne	0–2 m	58.8	600
		2–4 m	41.2	2100
		4–10 m	0.0	0
				Total: 2700
12	Mustinka	0–2 m	36.0	1700
		2–4 m	23.2	4000
		4–10 m	0.0	0
				Total: 5700
13	Otter Tail	0–2 m	37.4	400
		2–4 m	24.3	1200
		4–10 m	0	0
				Total: 1600
14	Park	0–2 m	165.0	6900
		2–4 m	125.0	16,700
		4–10 m	25.0	5600
				Total: 29,200
15	Pembina	0–2 m	90.7	3300
		2–4 m	66.3	8200
		4–10 m	5.4	4600
				Total: 16,100
16	Red Lake	0–2 m	68.1	12,400
		2–4 m	48.5	18,000
		4–10 m	0.0	0
				Total: 30,400
17	Roseau	0–2 m	48.9	5700
		2–4 m	33.4	6700
		4–10 m	0.0	0
				Total: 12,400
18	Sandhill–Wilson	0–2 m	125.9	16,400
		2–4 m	94.1	16,400
		4–10 m	14.7	4300
				Total: 37,100
19	Snake	0–2 m	43.6	2900
		2–4 m	29.2	4400
		4–10 m	0.0	0
				Total: 7300

Continued . . .

Table B-4. Breakdown of Storage (continued)

	Watershed	Relief, m	Average Storage Volume per Section, acre-ft	Average Storage Volume for all Sections, acre-ft	
20	Thief	0–2 m	39.2	9300	
		2–4 m	25.7	11,200	
		4–10 m	0.0	0	
					Total: 20,500
21	Turtle	0–2 m	89.3	2900	
		2–4 m	65.2	3300	
		4–10 m	5.1	500	
					Total: 6700
22	Two Rivers	0–2 m	54.0	6300	
		2–4 m	37.4	10,100	
		4–10 m	0.0	0	
					Total: 16,400
23	Upper Red	0–2 m	177.8	12,800	
		2–4 m	135.1	22,000	
		4–10 m	28.4	2200	
					Total: 37,000
24	Upper Sheyenne	0–2 m	147.2	100	
		2–4 m	111.0	1000	
		4–10 m	20.3	4600	
					Total: 5700
25	Western Wild Rice (ND)	0–2 m	89.0	10,500	
		2–4 m	65.0	14,400	
		4–10 m	5.0	3700	
					Total: 28,600
26	Wild Rice (MN)	0–2 m	96.9	5600	
		2–4 m	71.2	7600	
		4–10 m	7.1	2400	
					Total: 15,600
			RRB TOTAL:		**583,400**

categories. The resulting volumes were distributed to sections according to their relief classification. If any of the sections contained urban areas or were located within the 1997 floodplain, storage amounts were not assigned to them.

METHODOLOGY VALIDATION WITH LIGHT DETECTION AND RANGING (Lidar)

The methodology described above (a.k.a., NED/DRG method) was developed using the most up-to-date data sets for the RRB; however, the question still remained on how the results would vary if high-resolution elevation data were available. Therefore, in an attempt to validate the results, the EERC, with support from the Natural Resources Conservation Service mapping office in Texas, financed the collection of Lidar data for the Forest River Watershed. Aircraft equipped with Lidar transmit high-intensity light toward the ground during flight. As the light interacts with the ground, some of the light is reflected back to a receiver on the aircraft. The time for the light to travel to the target and back determines the distance between the target and the plane. Very advanced positioning equipment and ground reference points allow for the conversion of these distances to elevation data.

The Lidar data collected for the Forest River Watershed have a vertical accuracy of ±15 cm (5.9 inches) and a horizontal resolution of 1 meter (3.28 ft). Elevation data with a horizontal resolution of 1 meter are capable of differentiating raised roadbeds from the surrounding terrain, which was not possible with NED. Because of the large number of 1-meter grid cells (~ 2.26 billion), the Lidar data were resampled to a 3-meter grid, thereby reducing the number of grid cells to approximately 251 million. Raised roadbeds are still represented in the new grid as most roads are between 3.66 (single lane) and 9.15 meters (double lane) wide (i.e., 12 to 30 feet).

The ability to distinguish roadbeds in the elevation data provides an opportunity to estimate potential storage behind them. A hydrologic fill algorithm was performed on the Lidar data set to identify these areas and associated storage volumes. This is a means of calculating the storage volume in sinks using GIS. Figure B-8 illustrates the results of the hydrologic fill on the Forest River Watershed. The inherent nature of the data resulted in some unintended storage areas. For example, passages under bridges cannot be distinguished using the Lidar data set, and, as a result, the software artificially dammed water behind the bridges. Sinks associated with these artificial dams were removed if easily identifiable.

Conditions were imposed on the results from the hydrologic fill in order to improve volume estimates and isolate desired sinks. Because of data accuracy constraints, hydrologic sinks were limited to grid cells with depths greater than 20 cm. Sinks smaller than 10 acre-ft were removed from consideration (Figure B-9). Also, sinks associated with large water bodies and those falling within the boundaries of towns or rivers were eliminated from the group. The majority of sinks left after the application of these conditions were the result of roads (Figure B-10). Hence, these sinks could be used to provide an assessment of the Waffle storage potential for the Forest River Watershed.

The storage volumes for the remaining Lidar sinks were adjusted to account for a 1-ft freeboard around the roads. If the freeboard adjustment caused the capacity to drop below 10 acre-ft, these sinks were eliminated from the group. These adjusted storage volumes were summed together to provide an approximation of total storage potential for the watershed, which amounted to approximately 44,700 acre-ft. For comparison, the Forest River Watershed storage estimate before accounting for freeboard, natural storage, and the 1997 floodplain was 60,000 acre-ft. The moderate storage estimate, which considered 12.5 acre-ft of natural storage and a 30% volume reduction to account for freeboard, was 33,600 acre-ft. The most conservative estimate and the one ultimately modeled by the study was 8000 acre-ft. It appears that the NED methodology that includes reductions to account for freeboard, natural storage, and the 1997 floodplain may significantly underestimate water storage potential.

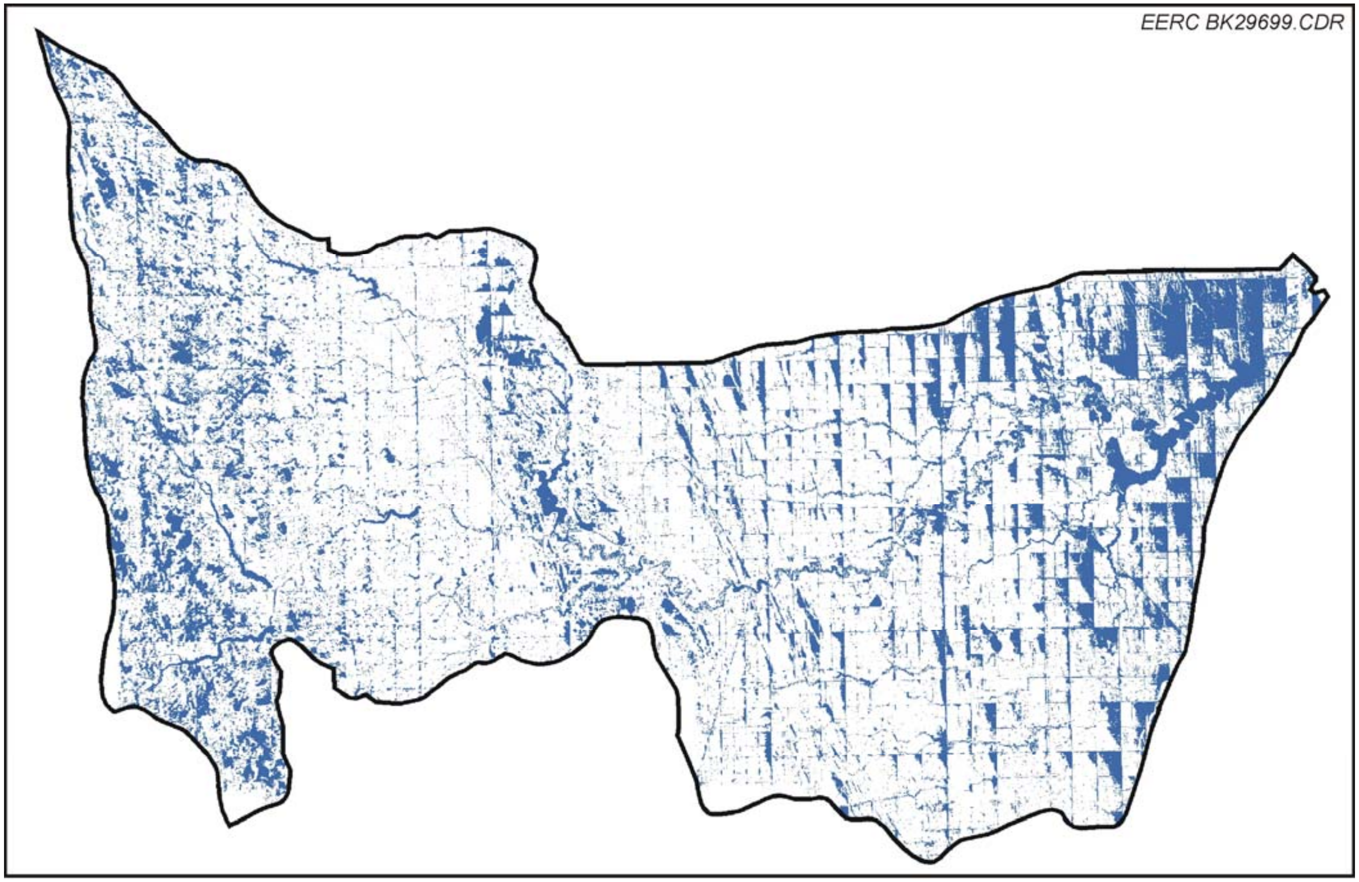


Figure B-8. Results from a hydrologic fill of the Forest River Watershed. Darkened areas represent sinks or areas of possible water storage. As illustrated on the image, this first attempt filled in several features that would not be considered Waffle storage.

Figure B-9. Example of sinks not applicable to Waffle storage. Darkened areas represent sinks. Results were adjusted so these areas were not included in storage estimates.

CAVEATS

Data crucial to the calculation of sinks include USGS 1-arc-second (~30 m) NED and the surveyed road elevations from the USGS 1:24,000 digital topographic maps. The NED data for the RRB was derived from Level 2 DEM data. Level 2 indicates the elevation data were acquired by contour digitization. Each contour line represents a line of equal elevation, and the lines are drawn according to survey points taken over a region. Consequently, the NED data are only as accurate as the contours which are dependent upon the accuracy of the surveyed points. The accuracy of the survey points is not known, but it can be assumed that they are more accurate than the NED. The maximum allowable error for Level 2 NED is half the contour interval (U.S. Geological Survey, 1947). For the RRB, the largest contour interval on a 1:24,000 scale topographic map is 20 feet, so the maximum allowed error would be ±10 feet or approximately ±3 meters.

In the extreme case where a NED grid cell is off by 3 meters, the change in volume above the cell is approximately 2.2 acre-ft. However, because errors are typically not limited to a single grid cell, the surrounding grid cells should have similar errors in elevation; therefore, relative changes in elevation (which was most important for this study) are more accurately reflected. Assuming the relative error (i.e., error between grid cells) is less than the absolute error in elevation, the argument can be made that elevation errors experienced by this study are less than ±3 meters.

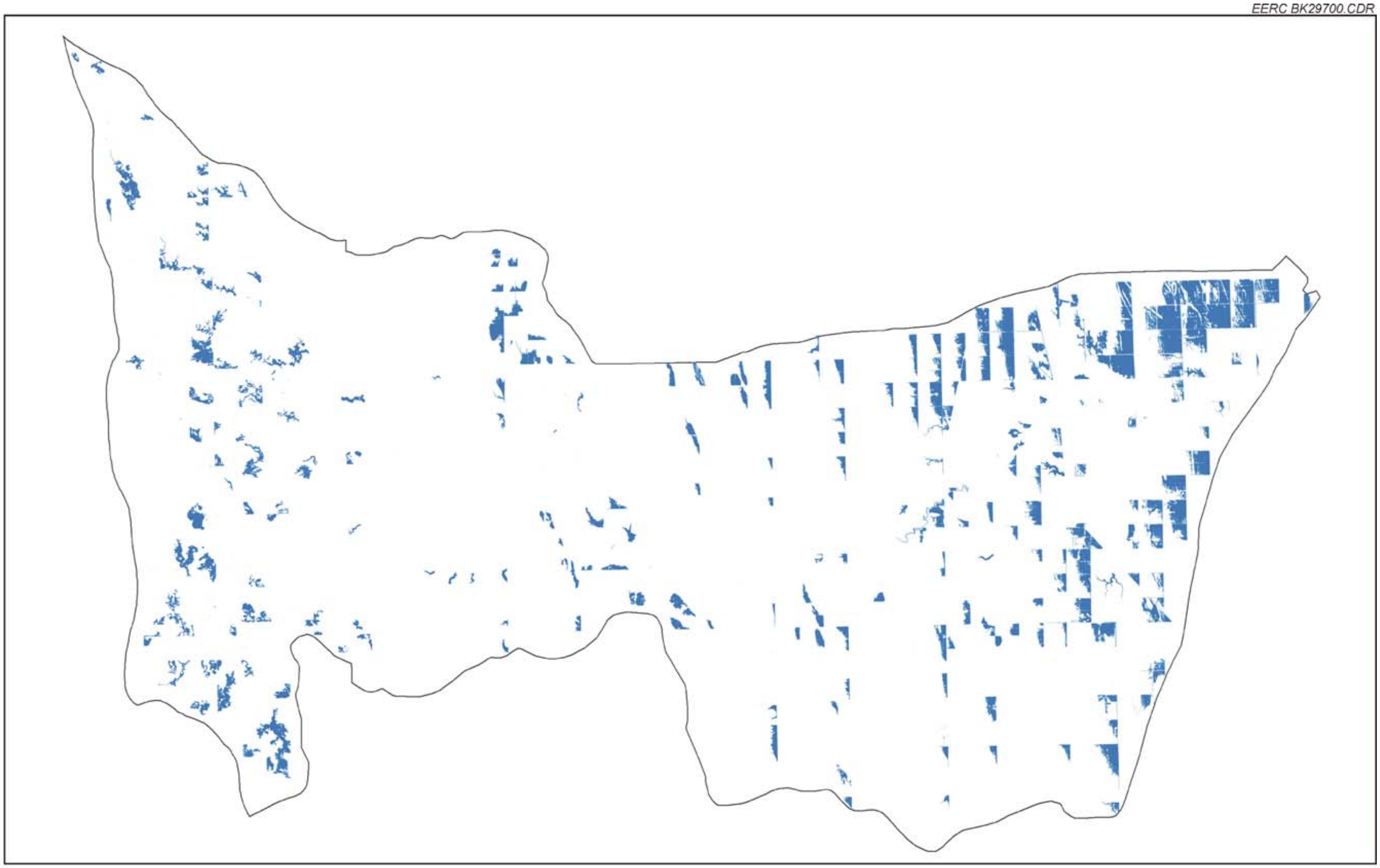


Figure B-10. The final representation of sinks for the Forest River Watershed. The darkened areas represent potential Waffle storage.

Spatially autocorrelated errors in elevation are errors shared between grid cells. Such errors have not been previously evaluated for the RRB. However, an estimate of the error can be made based on results from another study. A dissertation from State University of New York investigated the spatially autocorrelated errors for a NED data set for the Redland, California, Quadrangle (Wechsler, 2000). For relatively flat topography (standard deviation of elevation = 7 meters), the study determined the correlated errors between grid cells to be approximately 0.07% of the elevation. Applying this result to the RRB with a mean elevation of 1225 feet (373 meters), the uncertainty between grid cells is estimated to be ±0.86 feet (±0.26 meters). Based on this value, the so-called worst-case scenario would be an estimated water storage error of 546 acre-ft for a 640-acre PLSS section. Hence, the estimated water storage for a section can only claim accuracy to the nearest 100 acre-ft.

REFERENCES

Handbook of applied hydrology—a compendium of water-resources technology: Te Chow, V. (ed.), New York, McGraw Hill, 1964.

Sanocki, C., 2000, Using geographical information systems to identify potential water retention areas within the Wild Rice River Basin, northwestern Minnesota: U.S. Geological Survey draft document, 8 p.

U.S. Geological Survey, 1947, United States national map accuracy standards: Washington, D.C., Department of the Interior.

Wechsler, S., 2000, Effect of DEM uncertainty on topographic parameters, DEM scale, and terrain evaluation: Syracuse, New York, State University of New York College of Environmental Science and Forestry.

APPENDIX C

EVALUATION OF THE WAFFLE$^{®}$ FLOOD MITIGATION EFFECTS IN THE RED RIVER OF THE NORTH BASIN

EVALUATION OF THE WAFFLE® FLOOD MITIGATION EFFECTS IN THE RED RIVER OF THE NORTH BASIN

INTRODUCTION

Integrated Modeling Approach

Hydrologic and hydraulic models play a key role in evaluating the various structural and nonstructural flood mitigation measures proposed throughout the Red River Basin (RRB) (Halliday and Jutila, 2000; International Joint Commission, 1997). In the past decade, numerous models relevant to flood mitigation of the Red River have been developed. However, it would have been difficult and, in some cases, impossible to directly use these models to evaluate the Waffle concept because 1) they were developed for other objectives; 2) they have a different modeling scope, making it impossible for accurate comparison; 3) their parameters were not correlated with land use and other watershed management practices; and 4) they were not basinwide.

As a result, a new modeling approach for evaluation of the Waffle flood mitigation concept was necessary. This approach entailed coupling two different types of models to conduct the first comprehensive evaluation of a flood mitigation strategy for the entire RRB (Figure C-1). The first component of this approach was the development, calibration, and utilization of hydrologic models for 27 of the 28 watersheds in the U.S. portion of the RRB using the Soil and Water Assessment Tool (SWAT). These watersheds are defined by U.S. Geological Survey (USGS) 8-digit hydrologic unit codes (HUCs), and all except one drain into the Red River (Figure C-2 and Table C-1). The one watershed that does not drain into the Red River is Devils Lake; thus this watershed was not modeled as part of the Waffle project. Several of the watersheds, as defined by USGS, occur on both sides of the Red River. The hydrologic models were used to evaluate flow reductions in the RRB tributaries as a result of implementing Waffle storage throughout each watershed during a 1997-type flood event.

The second component of this approach was the evaluation of flood crest reductions along the Red River as a result of tributary flow reductions achieved by Waffle storage. This required the development and calibration of an unsteady-state (hydrodynamic) model, which was compiled using the Hydrologic Engineering Center's River Analysis System (HEC–RAS). The development of the HEC–RAS model was a joint effort with the U.S. Army Corps of Engineers (USACE).

Although this integrated modeling approach was developed for evaluation of Waffle storage, a similar approach could be used to evaluate a multitude of structural and nonstructural flood mitigation options throughout the RRB. Scenarios may include evaluation of structural measures such as improvements to existing detention ponds and culverts or construction of new impoundments or nonstructural measures such as adaptation of conservative agricultural practices, wetland restoration, creation of riparian zones, and use of existing temporary storage areas (De Laney, 1995; Napier et al., 1995). Using this approach and the models developed

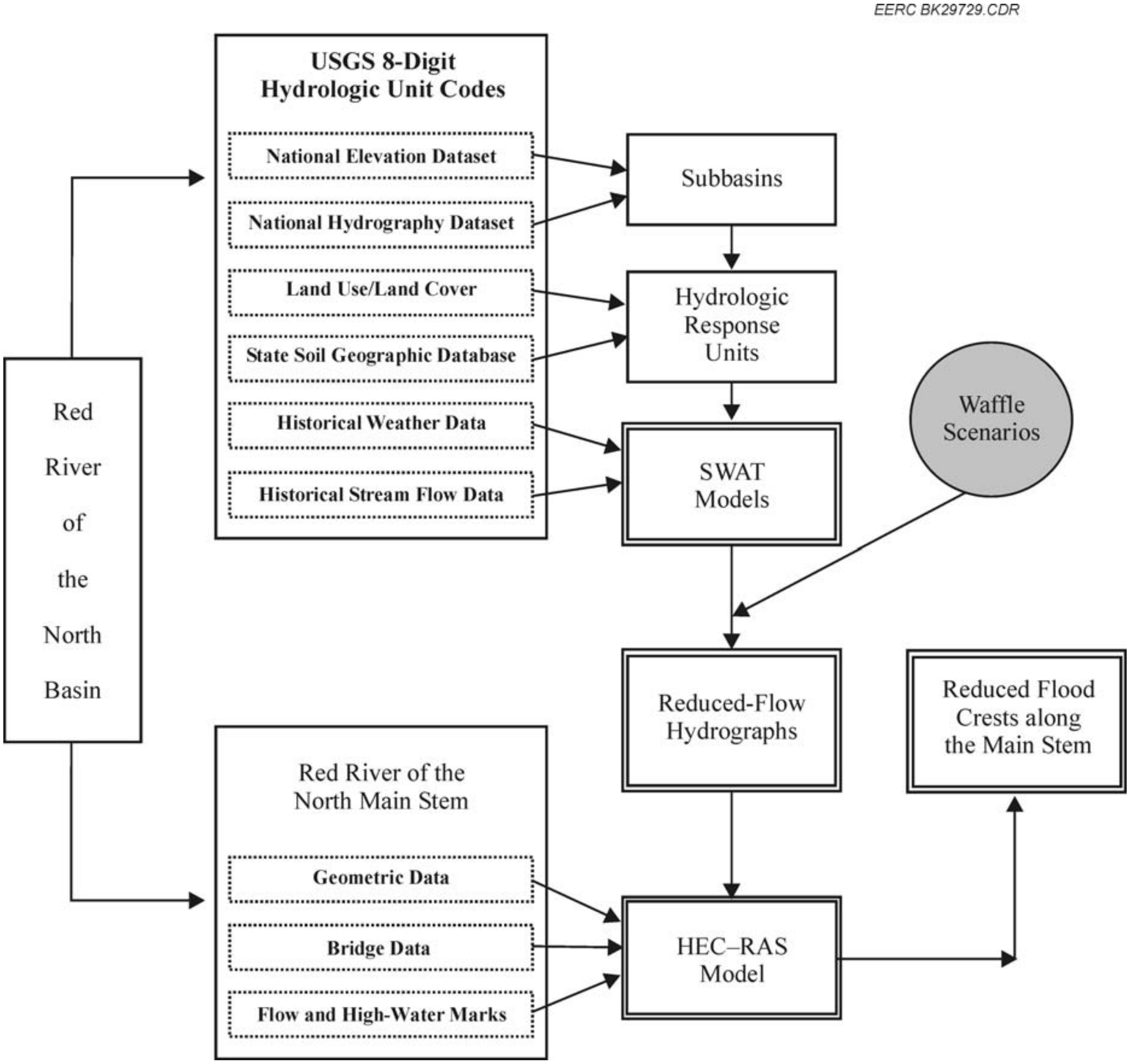


Figure C-1. The general framework of the integrated modeling approach for evaluating the effects of the Waffle on flood reduction.

through this project, any combination of structural and/or nonstructural options throughout the RRB could be evaluated to determine flow reductions along the Red River and its tributaries and corresponding stage reductions along the Red River. Although the conceptual modeling scheme utilizes SWAT and HEC–RAS, any hydrologic and/or hydrodynamic model pairing could be utilized, such as SWAT and MIKE-11.

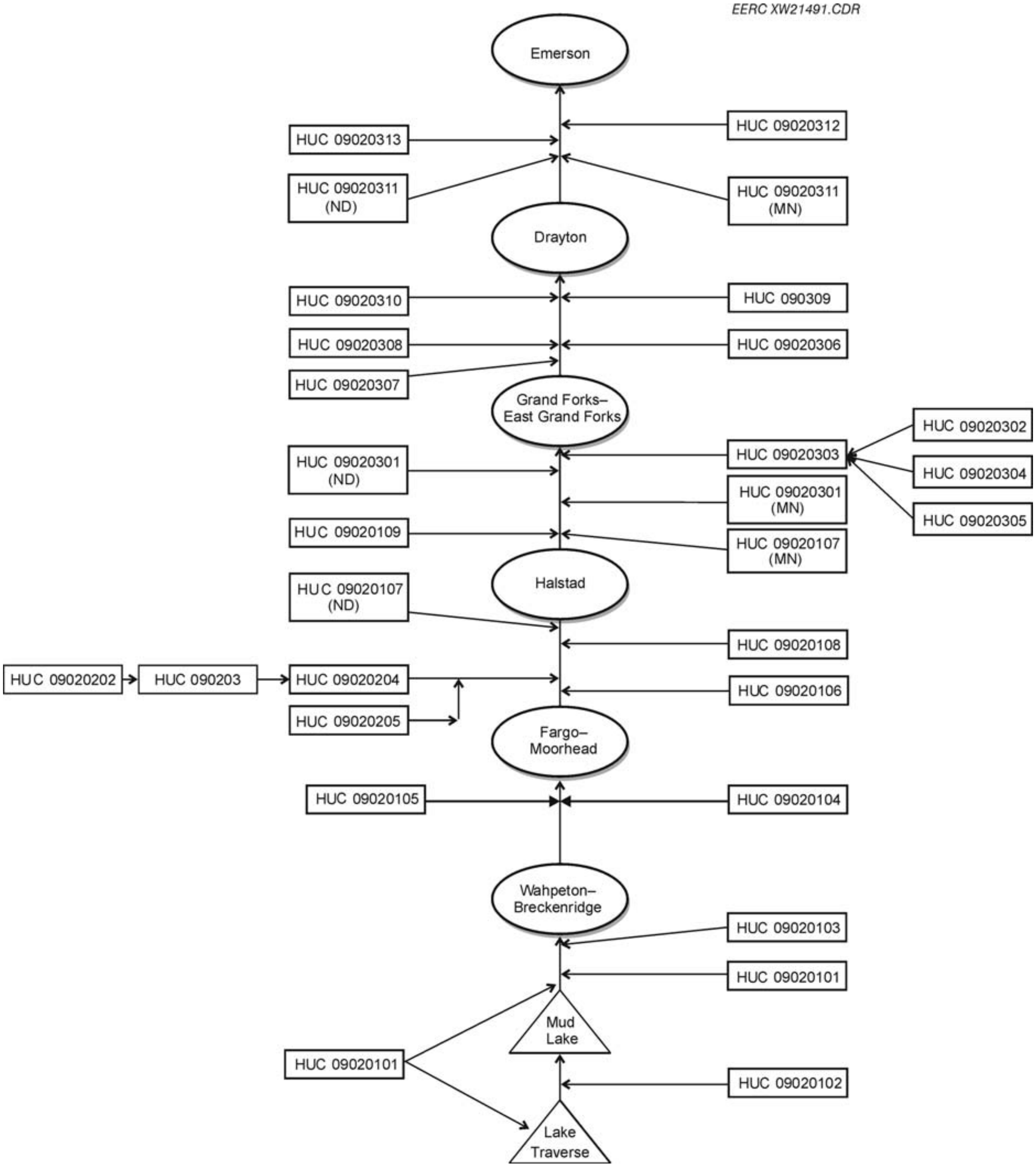


Figure C-2. Hydraulic connectivity of the HUCs that comprise the Red River of the North Basin.

Table C-1. HUCs Comprising the Red River of the North Basin

No.	HUC	Name	Drainage Area, mi^2	Administration Boundary
1	09020101	Bois de Sioux	1140	Minnesota, North Dakota
2	09020102	Mustinka	825	Minnesota
3	09020103	Otter Tail	1980	Minnesota
4	09020104	Upper Red	594	Minnesota, North Dakota
5	09020105	Western Wild Rice	2380	North Dakota
6	09020106	Buffalo	1150	Minnesota
7	09020107	Elm–Marsh	1150	Minnesota, North Dakota
8	09020108	Eastern Wild Rice	1670	Minnesota
9	09020109	Goose	1280	North Dakota
10	09020202	Upper Sheyenne	1940	North Dakota
11	09020203	Middle Sheyenne	2070	North Dakota
12	09020204	Lower Sheyenne	1640	North Dakota
13	09020205	Maple	1620	North Dakota
14	09020301	Sandhill–Wilson	1130	Minnesota, North Dakota
15	09020302	Red Lakes	2040	Minnesota
16	09020303	Red Lake	1450	Minnesota
17	09020304	Thief	994	Minnesota
18	09020305	Clearwater	1350	Minnesota
19	09020306	Grand Marais–Red	482	Minnesota, North Dakota
20	09020307	Turtle	714	North Dakota
21	09020308	Forest	875	North Dakota
22	09020309	Snake	953	Minnesota
23	09020310	Park	1080	North Dakota
24	09020311	Lower Red	1320	Minnesota, North Dakota
25	09020312	Two Rivers	958	Minnesota
26	09020313	Pembina	2020	North Dakota
27	09020314	Roseau	1230	Minnesota

Survey of Existing Models

Hydrologic and hydraulic models play a key role in evaluating and identifying economical and feasible measures for flood reduction in the RRB. In terms of complexity and modeling objectives, the models developed in the past two decades can be categorized as tools for 1) floodplain and floodway management analyses, 2) land planning and management analyses, 3) flood mitigation engineering design analyses, 4) flood forecasting, and 5) miscellaneous applications.

Floodplain and Floodway Management Analyses

In general, floodplain and floodway management analyses were conducted to meet the requirements of the National Flood Insurance Program (NFIP), established by the National Flood Insurance Act of 1968 and further defined by the Flood Disaster Protection Act of 1973 (Federal Emergency Management Agency, 1995a). Taking the peak discharge values with a 1% chance of being equaled or exceeded in any given year (100-year flood, or base flood), these analyses employ backwater steady-state hydraulic models to compute the corresponding water surface elevations (WSELs). The computed WSELs are superimposed on a topographic map with sufficient accuracy to delineate the base floodplain. Under certain circumstances, a floodway is determined and defined as the channel of a river or other watercourse and the adjacent land areas that must be reserved in order to discharge the base flood without cumulatively increasing the WSELs by more than a designated height such as 1.0 ft (0.3 m) (U.S. Army Corps of Engineers, 1992a, 2001a). With the available data, another three floods, termed as 10-, 50-, and 500-year floods with a 10%, 2%, and 0.2% chance, respectively, of being equaled or exceeded in any given year, were similarly analyzed. However, only a 500-year floodplain boundary was determined (Federal Emergency Management Agency, 2000). The peak discharge values used in these analyses were calculated either using a hydrologic rainfall–runoff model or a statistical computer program (U.S. Army Corps of Engineers, 1998a, 1992b, 2001b; Thomas et al., 1998; Interagency Advisory Committee on Water Data, 1982).

In the past decade, USACE conducted most of the hydrologic and hydraulic analyses to determine the base floodplain boundaries for both the main stem of the Red River and its major tributaries (Federal Emergency Management Agency, 1987, 1995b). The method of the Interagency Advisory Committee on Water Data (1982) was used to establish the peak discharge–frequency relationships, and HEC–2 and HEC–RAS models were developed to compute the WSELs. With updated observed data, USACE used the same method and completed a frequency analysis for the main stem of the Red River from Wahpeton, North Dakota, and Breckenridge, Minnesota, through Emerson, Manitoba (U.S. Army Corps of Engineers, 2001c). The results were used to update the flood insurance studies (FISs) for the relevant communities and counties.

Landscape Planning and Management Analyses

Bengtson et al. (1999) developed HEC–1 models to evaluate the effects of restoring drained wetlands on peak flood flows in the 1620-mi^2 (4200-m^2) Maple River Watershed and the 1670-mi^2 (4330-km^2) Eastern Wild Rice Watershed. In these models, the wetland storage was represented by flow diversions (U.S. Army Corps of Engineers, 1998a). The results indicated that restoring drained wetlands is highly unlikely to significantly affect the major floods. For the base flood, the peak flood flows may be reduced 3%–6%, resulting in only a 0.36%–0.85% lowered flood height. In parallel, Juliano and Simonovic (1999) employed the HEC–Hydrologic Modeling System (HMS) model to investigate the role of drained wetlands in reducing flood volume and peaks in the 598-mi^2 (1550-km^2) Rat River Watershed, approximately 20 mi (30 km) southeast of Winnipeg. Rather than studying frequency-based floods, they simulated six historical floods that occurred in 1950, 1974, 1979, 1986, 1996, and 1997. In this model, the wetland storage was also represented by flow diversions (U.S. Army Corps of Engineers, 2001b). Like Bengtson et al., Juliano and Simonovic concluded that while wetlands play a role in mitigating minor floods in this watershed, they have a negligible impact on the main stem of the Red River. Shultz (1999, 2000) drew similar conclusions from an economic standpoint.

To provide baseline and historical information for future research that will address specific water quality issues, Stoner et al. (1993) described the environmental setting of the RRB, including its physical, chemical, and aquatic–biological characteristics. The authors comprehensively used field experiments and observed data to quantify these characteristics and tackle their interrelationships. The analysis revealed that understanding the environmental setting of the RRB is necessary to develop reasonable goals for future water managment planning efforts that may help to mitigate flooding and improve water quality in the Red River.

Engineering Design Analyses

Hydrologic and hydraulic analyses were carried out to construct the six major dams along the Red River, including Lake Traverse, Mud Lake, Orwell, Baldhill, Red Lake, and Homme (www.mvp-wc.usace.army.mil). USACE conducted most of these analyses and maintains inventories of the models and other documents. In addition, hydraulic analyses used to design other infrastructure such as channel bypasses and dikes may be available from USACE, the U.S. Department of Transportation (DOT) in North Dakota and Minnesota, Manitoba Water Resources, and other agencies and companies.

To protect Grand Forks–East Grand Forks from flooding similar in scope to the 1997 flood, USACE (1998b) completed a general evaluation report for a proposed project consisting of 29.6 mi (47.7 km) of levees and a 2.1-mi (3.4-km) floodwall set back from the Red River, forming three rings around the two cities. A HEC–2 hydraulic model was used to determine the necessary length and height of the proposed levees and floodwall.

The structures in the RRB were designed mostly using designated design floods determined by frequency analyses. This widely-used method can be problematic if the data used in the frequency analyses cover a relatively short period of time when compared to major climatic fluctuations. Thus extreme floods or droughts may not always be represented by the data. To be conservative, the probable maximum flood (PMF) or the standard project flood (SPF) was sometimes taken as the design flood (U.S. Army Corps of Engineers, 1985; Lowing, 1995). The SPF is just a scaling down of the PMF (U.S. Army Corps of Engineers, 1960). Recognizing the inappropriateness of the PMF for the RRB (World Meteorological Organization, 1973; Sellars, 1999a), Warkentin (1999) suggested the hydrometeorologic parameter-routed flood (HPRT) to be the design flood. Adoption of the design floods based on these concepts will build a low-risk flood control system for the RRB.

Flood Forecasting

The National Weather Service (NWS) maintains and provides advanced hydrologic prediction services (AHPS) for the Red River (www.crh.noaa.gov/fgf). AHPS provides hydrologic forecasts with lead times from a few days to several months by not only accounting for precipitation already on the ground but also for probabilistic estimates of future precipitation. Both flow and stage hydrographs are predicted for 33 points on the Red River and its Minnesota and North Dakota tributaries, as well as for Devils Lake.

As part of the Corps Water Management System (CWMS), West Consultants Inc. (2002) developed a flood-forecasting system for the watershed upstream of the confluence of the Bois de Sioux River and Otter Tail River by integrating the distributed snow process model (DSPM) with the HEC–HMS, HEC–ResSim, and HEC–RAS models. The DSPM generates inputs for the distributed HEC–HMS model, including grid precipitation, temperature, and initial snow water equivalent. Output flow hydrographs from the HEC–HMS model are taken as the inputs into the

HEC–RAS and HEC–ResSim models to simulate the stage hydrographs for individual reaches and reservoirs, respectively.

Miscellaneous

Using gauged-flow hydrographs for ten historical major floods, McCombs-Knutson Associates Inc. (1984) developed a HEC–1 routing model to study the timing and volume contributions of a number of Minnesota tributaries to the main stem of the Red River. The main purpose of this study was to provide a general basis for assessing the potential effects of the proposed tributary reservoirs on main stem flood damage reduction from a flood-timing perspective. The results showed that the contributions varied from flood to flood; i.e., each of the ten historical major floods was routed by a HEC–1 model with different routing parameters or even different routing methods. Thus it is difficult to directly extrapolate these results to other floods. In 1988, USACE utilized the straddle-stagger or average-lag hydrologic routing method within the HEC–1 software package (U.S. Army Corps of Engineers, 1998a) to route the same ten historical flood hydrographs throughout the basin to points downstream. As with the McCombs-Knutson Associates Inc. study, this study revealed that the routing coefficients are flood-specific and, thus, updating the model requires determination of new routing coefficients. In addition, to provide information on the 1997 flood to both the public and relevant agencies, Houston Engineering Inc. (1999) analyzed in detail the contributions and timing of tributary and main stem flows to points downstream. They enhanced the 1988 study conducted by USACE and developed the routing coefficients appropriate for the 1997 flood. The analysis concluded that no single tributary is the source of large floods and no single dam will provide the solution to flooding of the Red River.

Complementing these hydrologic modeling efforts, several one-dimensional unsteady-state hydraulic models (hydrodynamic models) have been developed to simulate the flow and stage hydrographs along the main stem for the historical major floods, especially the 1997 flood. Zien (1997) developed a UNET (Unsteady NETwork) model to improve the analysis of flood conditions and to provide a planning tool for evaluating future levee alignment and elevation proposals in the RRB. He used the flow hydrograph at Lake Traverse as the upstream boundary condition and the stage hydrograph at Emerson as the downstream boundary condition. The data, including channel cross sections, bridges and culverts, and Manning's roughness coefficients used by USACE to conduct floodplain and floodway management analyses, were updated and used to develop the UNET model. Furthermore, Klohn–Crippen Consultants Ltd. (1999) developed a MIKE–11 hydrodynamic model to study the scenarios to operate the inlet control structure of the Red River floodway channel approximately 30 mi (48 km) long created to divert flooding from upstream to downstream of Winnipeg. The scenarios were analyzed for two synthetic 1826 floods and the 1997 flood. Sellars et al. (1999b, c) elaborated on model development and analysis results. The upstream boundary condition of the model is the gauged-flow hydrograph at Grand Forks, and the gauged-stage hydrograph at Selkirk is used as the downstream boundary condition. This MIKE–11 model incorporated very detailed topographic data for the Canadian portion but used the same data as the UNET model for the U.S. portion. Both of these models were summarized by Halliday and Jutila (2000). They indicated that neither the UNET model nor the MIKE–11 model would be affected by insufficient topographic data, variation and uncertainty of the boundary conditions, and poorly defined inflows from the ungauged areas; this view is shared by Waffle project personnel.

Like the UNET and MIKE–11 models, the FLDWAV (FLooD WAVe) model is a one-dimensional unsteady-state flow model, originally developed by NWS to determine the water surface profile of the dynamic wave downstream of a dam failure (Fread and Lewis, 1998). By 2000, NWS had completed a FLDWAV model for the Red River from the headwater reservoirs of Lake Traverse on the Bois de Sioux River and Orwell Lake on the Otter Tail River to Emerson. The model was designed for real-time flood routing and forecasting. It was calibrated using the 1997 and 1999 floods and verified using the 1996 flood. The peak stages were simulated to within 0.5 feet of the observed peak crests, with corresponding flows simulated to within 5% (Halliday and Jutila, 2000).

Description of SWAT

Overview

As previously mentioned, the conceptual modeling approach utilized by the EERC involved the use of the SWAT model. SWAT is a hydrologic model developed by the U.S. Department of Agriculture's (USDA's) Agricultural Research Service (ARS). It uses the physical characteristics of the landscape, such as soils, weather, land use, and topography, to predict the impact of land management practices on water, sediment, and agricultural chemical yields in watersheds over long periods of time (Neitsch et al., 2002a, b). SWAT was developed in the early 1990s to help water resource managers assess the impact of management and climate on water supplies and non-point-source pollution in small to large watersheds. Developed to "scale up" past field-scale models to large river basins, SWAT encompasses over 30 years of model development within USDA's ARS. SWAT is integrated with GIS (geographic information systems), groundwater models, and policy tools to evaluate alternative management scenarios and impact analysis of various existing and proposed natural resource management practices.

SWAT comprises two main components, namely, the land phase and the routing phase. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient, and pesticide loadings to the main channel in each subbasin based on the landscape characteristics (topography, land use, land cover, soil type, etc.) and weather conditions (Neitsch et al., 2002a). The second component, the water or routing phase, determines how water, sediment, and chemical constituents will be routed through the channel network to the watershed outlet (Neitsch et al., 2002a). Both the land phase and routing phase contain several subcomponents. For example, the land-phase component consists of eight subcomponents, namely, hydrology, weather, sedimentation, soil moisture, crop growth, nutrients, agricultural management, and pesticides. In turn, each of these subcomponents takes into account additional processes. For example, the hydrology subcomponent uses local climatic data to determine precipitation, evaporation, transpiration from vegetation, soil temperature, snow accumulation and melt, overland runoff, recharge to the subsurface, and surface water discharge (Figure C-3.) A detailed description of the SWAT model and its functions can be found on Texas A&M's SWAT Web site, (www.brc.tamus.edu/swat/index.html).

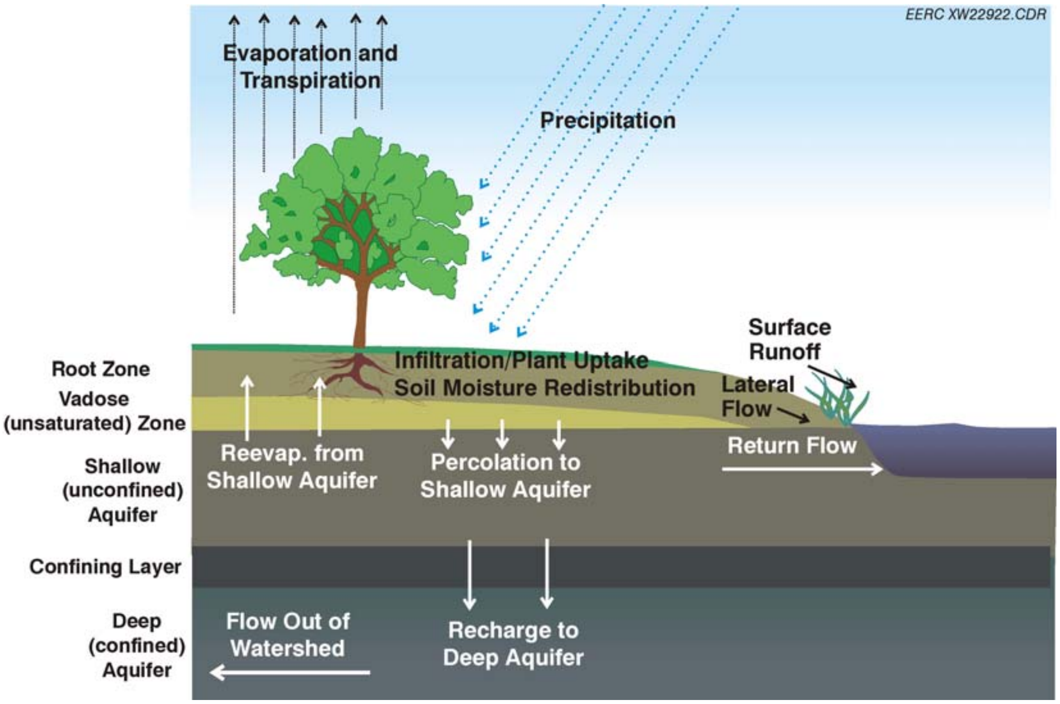


Figure C-3. Key processes considered in the hydrology component of SWAT (Neitsch et al., 2002a).

At the beginning of the Waffle study, hydrologic models were available for several Minnesota watersheds. These models were developed using the HEC–HMS. While the EERC initially considered using these models rather than developing new models using SWAT, the decision ultimately was to develop new models. The EERC's rationale for this is worth mentioning:

- While HEC–HMS needs fewer data and has been widely used to study water quantity, SWAT can be utilized to address a wider range of issues from water quantity to water quality.

- Although the hydrologic component of both models is comparable, SWAT has several advantages for flood reduction studies in the RRB. SWAT incorporates hydrologic response units (HRUs), portions of a subwatershed that possess unique land use–land management–soil attributes, which more accurately reflect the hydrologic characteristics of a study watershed. HRUs also allow for quantification of the hydrologic response of a particular landscape to changes in agricultural or land management practices.

- SWAT has a more comprehensive function for simulating small ponds and wetlands, which includes processes such as infiltration and evaporation. These components are well-suited for evaluating the Waffle concept and would allow Waffle storage areas to be simulated as either ponds or intermittent wetlands. On the other hand, HEC–HMS has been traditionally used to simulate big dams.

- SWAT simulates runoff produced both by rainfall and snowfall in one run. Its snowfall component simulates snow accumulation and snow thaw, which is very convenient when the snowmelt-dominated flooding in the RRB is studied. Conversely, when HEC–HMS is used, a separate snow model is needed to convert the snowfall to the equivalent rainfall hyetographs needed for input (Shutov, 2000; Socolofsky et al., 2001).

- SWAT subdivides the vadose zone into several sublayers. The soil moisture and permeability affecting the infiltration into the vadose zone may be specified for each of the layers to more accurately consider antecedent conditions, one of the five constant factors leading to a casual flood (Bluemle, 1997). The recharge from the vadose zone into groundwater may be accurately simulated by the SWAT model.

- SWAT includes a water quality component. In addition to water yield, SWAT can simulate sediment and chemical loading, as well as crop yields corresponding to various weather conditions and alternative agricultural practices.

- SWAT has been seamlessly integrated with the databases developed and maintained by several federal agencies, including USGS, USDA, and the U.S. Environmental Protection Agency (EPA), which will undoubtedly expedite model development, standardization, usage, and upgrading. For example, the model parameters initially used can be automatically extracted from these databases and then adjusted for the study watershed to develop a calibrated and verified model.

Key SWAT Components

A description of the processes most relevant to evaluation of the Waffle concept in the RRB are described below. In the Waffle project, the Soil Conservation Service (SCS) runoff curve number, adjusted according to soil moisture conditions, was used to estimate surface runoff, the Priestley–Taylor method used to estimate potential evapotranspiration, and the Muskingum method used for channel routing. Because SWAT was used to simulate the spring snowmelt flooding in this project, the subcomponents of snowmelt hydrology, pond routing, and the Muskingum channel routing are described below.

Snowmelt Hydrology

In SWAT, snowmelt hydrology is realized on an HRU basis. A watershed is subdivided into a number of subbasins for modeling purposes. Portions of a subbasin that possess unique land use/management/soil attributes are grouped together and defined as one HRU. Depending on data availability and modeling accuracy, one subbasin may have one or several HRUs defined. When the mean daily air temperature is less than the snowfall temperature, as specified by the variable (SFTMP), the precipitation within an HRU is classified as snow and the liquid water equivalent of the snow precipitation is added to the snowpack.

The snowpack increases with additional snowfall, but decreases with snowmelt or sublimation. The mass balance for the snowpack is computed as:

$$SNO_i = SNO_{i-1} + R_{sfi} - E_{subi} - SNO_{mlti} \qquad \text{[Eq. 1]}$$

where SNO_i and SNO_{i-1} are the water equivalents of the snowpack on the current day (i) and previous day (i-1), respectively, R_{sfi} is the water equivalent of the snow precipitation on day i, E_{subi} is the water equivalent of the snow sublimation on day i, and SNO_{mlti} is the water equivalent of the snowmelt on day i. All of these variables are reported in terms of the equivalent water depth (mm) over the total HRU area.

The snowpack is rarely uniformly distributed over the total area, resulting in a fraction of the area that is bare of snow. In SWAT, the areal coverage of snow over the total HRU area is defined using an areal depletion curve, which describes the seasonal growth and recession of the snowpack and is defined as:

$$sno_{\mathrm{cov}\,i} = \frac{SNO_i}{SNOCOVMX}\left[\frac{SNO_i}{SNOCOVMX} + \exp(\mathrm{cov}_1 - \mathrm{cov}_2 \cdot \frac{SNO_i}{SNOCOVMX})\right]^{-1} \qquad \text{[Eq. 2]}$$

where $sno_{\mathrm{cov}i}$ is the fraction of the HRU area covered by snow on the current day (i), SNOCOVMX is the minimum snow water content that corresponds to 100% snow cover (mm H_2O), and cov_1 and cov_2 are the coefficients that define the shape of the curve. The values used for cov_1 and cov_2 are determined by solving Equation 2 using two known points: 1) 95% coverage at 95% SNOCOVMX and 2) 50% coverage at a fraction of SNOCOVMX, specified by the variable SNO50COV. For example, assuming that SNO50COV is equal to 0.2, cov_1 and cov_2 will take the values of −1.2399 and 1.8482, respectively.

The value of $sno_{\mathrm{cov}i}$ is assumed to be equal to 1.0 once the water content of the snowpack exceeds SNOCOVMX, indicating a uniform depth of snow over the HRU area. The areal depletion curve affects snowmelt only when the snowpack water content is between 0.0 and SNOCOVMX. Consequently, a small value for SNOCOVMX will assume a minimal impact of the areal depletion curve on snowmelt, whereas as the value of SNOCOVMX increases, the curve will assume a more important role in approximating the snowmelt process.

In addition to the areal coverage of snow, snowmelt is also controlled by the snowpack temperature and melting rate. The snowpack temperature is a function of the mean daily temperature during the preceding days and varies as a dampened function of air temperature. The influence of the previous day's snowpack temperature on the current day's snowpack temperature is described by a lag factor, specified by the variable TIMP, which implicitly accounts for snowpack density, water content, and exposure. The snowpack temperature is calculated as:

$$T_{spi} = T_{spi-1}(1 - TIMP) + \overline{T}_{ai} \cdot TIMP \qquad \text{[Eq. 3]}$$

where T_{spi} and T_{spi-1} are the snowpack temperatures on the current day (i) and the previous day (i-1), respectively, and $\overline{T}_{ai}$ is the mean air temperature on day i. As TIMP approaches 1.0, $\overline{T}_{ai}$ exerts an increasingly greater influence on T_{spi}; conversely, as TIMP moves away from 1.0, T_{spi-1} becomes more important.

The amount of snowmelt on the current day (i), $\mathrm{SNO}_{\mathrm{mlt}i}$, expressed in terms of the equivalent amount of water in mm, or melting rate, is calculated in SWAT as:

$$\mathrm{SNO}_{\mathrm{mlt}i} = b_{\mathrm{mlt}i} \cdot sno_{\mathrm{cov}i} \left(\frac{\mathrm{T}_{\mathrm{sp}i} + \mathrm{T}_{\mathrm{max}i}}{2} - \mathrm{SMTMP} \right) \qquad \text{[Eq. 4]}$$

where $\mathrm{T}_{\mathrm{max}i}$ is the maximum air temperature on day i (°C), SMTMP is the base temperature above which snowmelt is allowed (°C), and $b_{\mathrm{mlt}i}$ is the melt factor on day i (mm H_2O/°C-day), which is calculated as:

$$\mathrm{b}_{\mathrm{mlti}} = \frac{\mathrm{SMFMX} + \mathrm{SMFMN}}{2} + \frac{\mathrm{SMFMX} - \mathrm{SMFMN}}{2} \cdot \sin\left[\frac{2\pi}{365} (\mathrm{i} - 81) \right] \qquad \text{[Eq. 5]}$$

where SMFMX and SMFMN are the maximum and minimum snowmelt factors, respectively (mm H_2O/°C-day).

Pond Routing

In SWAT, a pond is defined within a subbasin to receive inflow from a fraction of the subbasin area. Thus ponds can be used to appropriately mimic the hydrologic functions of Waffle storages. The water balance for a pond is:

$$\mathrm{V} = \mathrm{V}_{\mathrm{stored}} + \mathrm{V}_{\mathrm{flowin}} - \mathrm{V}_{\mathrm{flowout}} + \mathrm{V}_{\mathrm{pcp}} - \mathrm{V}_{\mathrm{evap}} - \mathrm{V}_{\mathrm{seep}} \qquad \text{[Eq. 6]}$$

where V is the volume of water in the pond at the end of the day (m^3 H_2O), $\mathrm{V}_{\mathrm{stored}}$ is the volume of water stored in the pond at the beginning of the day (m^3 H_2O), $\mathrm{V}_{\mathrm{flowin}}$ is the volume of water entering the pond during the day (m^3 H_2O), $\mathrm{V}_{\mathrm{flowout}}$ is the volume of water flowing out of the pond during the day (m^3 H_2O), $\mathrm{V}_{\mathrm{pcp}}$ is the volume of precipitation falling in the pond during the day (m^3 H_2O), $\mathrm{V}_{\mathrm{evap}}$ is the volume of water removed from the pond by evaporation during the day (m^3 H_2O), and $\mathrm{V}_{\mathrm{seep}}$ is the volume of water lost from the pond by seepage (m^3 H_2O).

To estimate the terms in Equation 6, SWAT updates the surface area in a daily time step using the equation:

$$\mathrm{SA} = \beta_{\mathrm{sa}} \cdot \mathrm{V}^{\mathrm{exp\,sa}} \qquad \text{[Eq. 7]}$$

where SA is the surface area of the pond (ha), β_{sa} is a coefficient, and expsa is an exponent. Expsa and β_{sa} are computed as:

$$\mathrm{expsa} = \frac{\log_{10}(\mathrm{SA}_{\mathrm{em}}) - \log_{10}(\mathrm{SA}_{\mathrm{pr}})}{\log_{10}(\mathrm{V}_{\mathrm{em}}) - \log_{10}(\mathrm{V}_{\mathrm{pr}})} \qquad \text{[Eq. 8]}$$

$$\beta_{sa} = \frac{SA_{em}}{V_{em}^{expsa}} \quad \text{[Eq. 9]}$$

where SA_{em} is the surface area of the pond when filled to the emergency spillway (ha), SA_{pr} is the surface area of the pond when filled to the principal spillway (ha), V_{em} is the volume of water held in the pond when filled to the emergency spillway (m^3 H_2O), and V_{pr} is the volume of water held in the pond when filled to the principal spillway (m^3 H_2O).

V_{pcp} is computed as:

$$V_{pcp} = 10 \cdot R_{day} \cdot SA \quad \text{[Eq. 10]}$$

where R_{day} is the amount of precipitation falling during the day (mm H_2O).

V_{flowin} is computed as:

$$V_{flowin} = fr_{imp} \cdot 10 \cdot (Q_{surf} + Q_{gw} + Q_{lat}) \cdot (A_{sub} - SA) \quad \text{[Eq. 11]}$$

where fr_{imp} is the fraction of the subbasin area draining into the pond, Q_{surf} is the surface runoff from the subbasin during the day (mm H_2O), Q_{gw} is the groundwater flow generated in the subbasin during the day (mm H_2O), Q_{lat} is the lateral flow generated in the subbasin during the day (mm H_2O), and A_{sub} is the subbasin area (ha).

V_{evap} is computed as:

$$V_{evap} = 10 \cdot \eta \cdot E_0 \cdot SA \quad \text{[Eq. 12]}$$

where η is an evaporation coefficient with a default value of 0.6, and E_0 is the potential evapotranspiration for the day (mm H_2O).

V_{seep} is computed as:

$$V_{seep} = 240 \cdot K_{sat} \cdot SA \quad \text{[Eq. 13]}$$

where K_{sat} is the effective saturated hydraulic conductivity of the pond bottom (mm/hr).

$V_{flowout}$ is computed as:

$$V_{flowout} = \frac{V - V_{targ}}{ND_{targ}} \quad \text{[Eq. 14]}$$

where V_{targ} is the target pond volume for the day (m^3 H_2O), and ND_{targ} is the number of days required for the pond to reach the target volume.

To model the storage and release process of the Waffle; i.e., the water is stored for specified days and then released in the following days, the SWAT algorithm for computing V_{targ} was revised as:

$$V_{targ} = \begin{cases} V_{em} & \text{if } jday_{stor,beg} \le jday \le jday_{stor,end} \\ 0 & \text{otherwise} \end{cases} \qquad \text{[Eq. 15]}$$

where $jday_{stor,beg}$ is the beginning Julian day of storage, $jday_{stor,end}$ is the end Julian day of storage, and jday is the current simulating Julian day.

Muskingum Channel Routing

The Muskingum routing method models the storage volume in a channel length as a combination of wedge and prism storage. When a flood wave advances into a reach segment, inflow exceeds outflow and a wedge of storage is produced. As the flood wave recedes, outflow exceeds inflow in the reach segment, and a negative wedge is produced. In addition to the wedge storage, the reach segment contains a prism of storage formed by a volume of constant cross section along the reach length. For a simulation day, the outflow is computed as:

$$q_{out,i+1} = C_1 \cdot q_{in,i+1} + C_2 \cdot q_{in,i} + C_3 \cdot q_{out,i} \qquad \text{[Eq. 16]}$$

where $q_{in,i}$ is the inflow rate at day i (m^3/s), $q_{in,i+1}$ is the inflow rate at day i+1 (m^3/s), $q_{out,i}$ is the outflow rate at day i (m^3/s), $q_{out,i+1}$ is the outflow at day i+1 (m^3/s), and C_1, C_2, C_3 are coefficients with a summation of unity, i.e., $C_1 + C_2 + C_3 = 1$, and are computed as:

$$C_1 = \frac{\Delta t - 2 \cdot K \cdot X}{2 \cdot K \cdot (1 - X) + \Delta t} \qquad \text{[Eq. 17]}$$

$$C_2 = \frac{\Delta t + 2 \cdot K \cdot X}{2 \cdot K \cdot (1 - X) + \Delta t} \qquad \text{[Eq. 18]}$$

$$C_3 = \frac{2 \cdot K \cdot (1 - X) - \Delta t}{2 \cdot K \cdot (1 - X) + \Delta t} \qquad \text{[Eq. 19]}$$

where K is the ratio of storage to outflow (s), X is a weighting factor that controls the relative importance of inflow and outflow in determining the storage in a reach, and Δt is the simulation time step (i.e., 1 day). To maintain numerical stability and avoid the commutation of negative outflows, the following condition must be met:

$$2 \cdot K \cdot X \le \Delta t \le 2 \cdot K \cdot (1 - X) \qquad \text{[Eq. 20]}$$

K is computed as:

$$K = coef_1 \cdot K_{bnkfull} + coef_2 \cdot K_{0.1bnkfull} \qquad \text{[Eq. 21]}$$

where coef_1 and coef_2 are weighting coefficients, K_{bnkfull} is the storage time constant calculated for the reach segment with the bankfull flow (s), and $K_{0.1\mathrm{bnkfull}}$ is the storage time constant calculated for the reach segment with one-tenth of the bankfull flow (s).

K_{bnkfull} is computed as:

$$K_{\mathrm{bnkfull}} = \frac{1000 \cdot L_{\mathrm{ch,bnkfull}}}{c_{\mathrm{k,bnkfull}}} \qquad \text{[Eq. 22]}$$

where $L_{\mathrm{ch,bnkfull}}$ is the channel length at the bankfull flow (km), and $c_{\mathrm{k,bnkfull}}$ is the celerity at the bankfull flow, i.e., the velocity with which a variation in flow rate travels along the channel.

$c_{\mathrm{k,bnkfull}}$ is computed as:

$$c_{\mathrm{k,bnkfull}} = \frac{5}{3} \cdot v_{\mathrm{bnkfull}} \qquad \text{[Eq. 23]}$$

where v_{bnkfull} is the flow velocity at the bankfull flow and computed using the Manning's equation.

$K_{0.1\mathrm{bnkfull}}$ is computed as:

$$K_{0.1\mathrm{bnkfull}} = \frac{1000 \cdot L_{\mathrm{ch,0.1bnkfull}}}{c_{\mathrm{k,0.1bnkfull}}} \qquad \text{[Eq. 24]}$$

where $L_{\mathrm{ch,0.1bnkfull}}$ is the channel length at one-tenth of the bankfull flow (km), and $c_{\mathrm{k,0.1bnkfull}}$ is one-tenth of the celerity at the bankfull flow, i.e., the velocity with which a variation in flow rate travels along the channel.

$c_{\mathrm{k,0.1bnkfull}}$ is computed as:

$$c_{\mathrm{k,0.1bnkfull}} = \frac{5}{3} \cdot v_{0.1\mathrm{bnkfull}} \qquad \text{[Eq. 25]}$$

where $v_{0.1\mathrm{bnkfull}}$ is the flow velocity at one-tenth of the bankfull flow and computed using Manning's equation.

Description of HEC–RAS

HEC–RAS is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. The current version of HEC–RAS supports steady and unsteady flow water surface profile calculations. The hydraulic calculations for cross sections, bridges, culverts, and other hydraulic structures that were developed for the steady flow component were incorporated into the unsteady flow module. The unsteady flow module has the ability to model storage areas and hydraulic connections between storage areas as well as between stream reaches. However, this module was developed primarily for subcritical flow regime calculations.

Assuming a horizontal water surface at each cross section normal to the direction of flow, i.e., a negligible exchange of momentum between the channel and floodplain, HEC–RAS distributes the discharge according to conveyance and solves a set of one-dimensional equations expressed as:

$$\frac{\partial A}{\partial t} + \frac{\partial(\phi \cdot Q)}{\partial x_c} + \frac{\partial[(1-\phi)\cdot Q]}{\partial x_f} = 0 \qquad \text{[Eq. 26]}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial(\phi^2 \cdot Q^2 / A_c)}{\partial x_c} + \frac{\partial[(1-\phi)^2 \cdot Q^2 / A_f]}{\partial x_f} + g \cdot A_c\left[\frac{\partial Z}{\partial x_c} + S_{fc}\right] + g \cdot A_f\left[\frac{\partial Z}{\partial x_f} + S_{ff}\right] = 0 \qquad \text{[Eq. 27]}$$

where Q is the total flow, Z is the water surface elevation, the subscripts c and f refer to the channel and floodplain, respectively, and ϕ is the ratio of the channel conveyance to the total conveyance (i.e., the summation of the channel conveyance and floodplain conveyance).

Equations 26 and 27 are solved using the four-point implicit scheme, also known as the box scheme. With this scheme, Equation 26 has a finite difference form expressed as:

$$\Delta Q + \frac{\Delta A_c}{\Delta t}\cdot(\Delta x_c) + \frac{\Delta A_f}{\Delta t}\cdot(\Delta x_f) + \frac{\Delta S}{\Delta t}\cdot(\Delta x_f) - \overline{Q}_L = 0 \qquad \text{[Eq. 28]}$$

where $\overline{Q}_L$ is the average lateral inflow.

Equation 27 has a finite difference form expressed as:

$$\frac{\Delta(Q_c \cdot \Delta x_c + Q_f \cdot \Delta x_f)}{\Delta t \cdot \Delta x_e} + \frac{\Delta(\beta \cdot V \cdot Q)}{\Delta x_e} + g \cdot \overline{A}\left(\frac{\Delta z}{\Delta x_e} + \overline{S}_f + \overline{S}_h\right) = \xi \cdot \frac{Q_L \cdot V_L}{\Delta x_e} \qquad \text{[Eq. 29]}$$

where Q_L is the lateral inflow, V_L is the average velocity of the lateral inflow, ξ is the fraction of the momentum entering the receiving stream, $\overline{A}$ is equal to $\overline{A}_c + \overline{A}_f$, $\overline{S}_f$ is the friction slope for the entire section, and Δx_e is the equivalent flow path computed as:

$$\Delta x_e = \frac{\overline{A}_c \cdot \overline{S}_{fc} \cdot \Delta x_c + \overline{A}_f \cdot \overline{S}_{ff} \cdot \Delta x_f}{\overline{A} \cdot \overline{S}_f} \qquad \text{[Eq. 30]}$$

The convective term β is defined as:

$$\beta = \frac{V_c \cdot Q_c + V_f \cdot Q_f}{V \cdot Q} \qquad \text{[Eq. 31]}$$

$\overline{S}_h$ is the rate of energy loss caused by structures such as bridge piers, navigation dams, and cofferdams and is computed as:

$$\overline{S}_h = \frac{h_L}{\Delta x_e} \qquad \text{[Eq. 32]}$$

where h_L is the head loss. Within HEC–RAS, the steady flow bridge and culvert routines are used to compute a family of rating curves for the structure. During the simulation, for a given flow and tailwater, a resulting headwater elevation is interpolated from the curves. The difference between the headwater and tailwater is set to h_L.

Using the Preissmann technique, for a computation reach from node j to j+1, Equations 28 and 29 are linearized as:

$$CQ1_j \cdot \Delta Q_j + CZ1_j \cdot \Delta z_j + CQ2_j \cdot \Delta Q_{j+1} + CZ2_j \cdot \Delta z_{j+1} = CB_j \qquad \text{[Eq. 33]}$$

$$MQ1_j \cdot \Delta Q_j + MZ1_j \cdot \Delta z_j + MQ2_j \cdot \Delta Q_{j+1} + MZ2_j \cdot \Delta z_{j+1} = MB_j \qquad \text{[Eq. 34]}$$

where

$$CQ1_j = \frac{-\theta}{\Delta x_{ej}} \qquad \text{[Eq. 35]}$$

$$CZ1_j = \frac{0.5}{\Delta t \cdot \Delta x_{ej}} \left[\left(\frac{dA_c}{dz} \right)_j \cdot \Delta x_{cj} + \left(\frac{dA_f}{dz} + \frac{dS}{dz} \right)_j \cdot \Delta x_{fj} \right] \qquad \text{[Eq. 36]}$$

$$CQ2_j = \frac{\theta}{\Delta x_{ej}} \qquad \text{[Eq. 37]}$$

$$CZ2_j = \frac{0.5}{\Delta t \cdot \Delta x_{ej}} \left[\left(\frac{dA_c}{dz} \right)_{j+1} \cdot \Delta x_{cj} + \left(\frac{dA_f}{dz} + \frac{dS}{dz} \right)_{j+1} \cdot \Delta x_{fj} \right] \qquad \text{[Eq. 38]}$$

$$CB_j = -\frac{Q_{j+1} - Q_j}{\Delta x_{ej}} + \frac{Q_L}{\Delta x_{ej}} \qquad \text{[Eq. 39]}$$

$$MQ1_j = 0.5 \frac{\Delta x_{cj} \cdot \phi_j + \Delta x_{fj} \cdot (1 - \phi_j)}{\Delta x_{ej} \cdot \Delta t} - \frac{\beta_j \cdot V_j \cdot \theta}{\Delta x_{ej}} + \theta \cdot g \cdot \overline{A} \frac{S_{fj} + S_{hj}}{Q_j} \qquad \text{[Eq. 40]}$$

$$MZ1_j = -\frac{g\cdot\bar{A}\cdot\theta}{\Delta x_{ej}} + 0.5\cdot g\cdot(z_{j+1}-z_j)\left(\frac{dA}{dz}\right)_j\left(\frac{\theta}{\Delta x_{ej}}\right) - g\cdot\theta\cdot\bar{A}\left[\left(\frac{dK}{dz}\right)_j\left(\frac{S_{fj}}{K_j}\right)+\left(\frac{dA}{dz}\right)_j\left(\frac{S_{hj}}{A_j}\right)\right] \qquad \text{[Eq. 41]}$$
$$+0.5\cdot\theta\cdot g\left(\frac{dA}{dz}\right)_j\left(\bar{S}_f+\bar{S}_h\right)$$

$$MQ2_j = 0.5\frac{\Delta x_{cj+1}\cdot\phi_{j+1}+\Delta x_{fj+1}\cdot(1-\phi_{j+1})}{\Delta x_{ej}\cdot\Delta t} + \frac{\beta_{j+1}\cdot V_{j+1}\cdot\theta}{\Delta x_{ej}} + \theta\cdot g\cdot\bar{A}\frac{S_{fj+1}+S_{hj+1}}{Q_{j+1}} \qquad \text{[Eq. 42]}$$

$$MZ2_j = -\frac{g\cdot\bar{A}\cdot\theta}{\Delta x_{ej}} + 0.5\cdot g\cdot(z_{j+1}-z_j)\left(\frac{dA}{dz}\right)_{j+1}\left(\frac{\theta}{\Delta x_{ej}}\right) - g\cdot\theta\cdot\bar{A}\left[\left(\frac{dK}{dz}\right)_{j+1}\left(\frac{S_{fj+1}}{K_{j+1}}\right)+\left(\frac{dA}{dz}\right)_{j+1}\left(\frac{S_{hj+1}}{A_{j+1}}\right)\right] \qquad \text{[Eq. 43]}$$
$$+0.5\cdot\theta\cdot g\left(\frac{dA}{dz}\right)_{j+1}\left(\bar{S}_f+\bar{S}_h\right)$$

$$MB_j = -\left[\left(\beta_{j+1}\cdot V_{j+1}\cdot Q_{j+1}-\beta_j\cdot V_j\cdot Q_j\right)\left(\frac{1}{\Delta x_{ej}}\right)+\left(\frac{g\cdot\bar{A}}{\Delta x_{ej}}\right)\left(z_{j+1}-z_j\right)+g\cdot\bar{A}\left(\bar{S}_f+\bar{S}_h\right)\right] \qquad \text{[Eq. 44]}$$

$$\phi_j = \frac{K_{cj}}{K_{cj}+K_{fj}} \qquad \text{[Eq. 45]}$$

$$\Delta x_{ej} = \frac{(A_{cj}+A_{cj+1})\Delta x_{cj}+(A_{fj}+A_{fj+1})\Delta x_{fj}}{A_j+A_{j+1}} \qquad \text{[Eq. 46]}$$

For a junction, HEC–RAS applies flow continuity to reaches upstream of flow splits and downstream of flow combinations, whereas stage continuity is used for all other reaches. In addition, upstream boundary conditions are required at the upstream end of all reaches that are not connected to other reaches or storage areas. An upstream boundary condition is applied as a flow hydrograph of discharge versus time. On the other hand, downstream boundary conditions are required at the downstream end of all reaches which are not connected to other reaches or storage areas. In this study, a single-valued rating curve and/or normal depth from Manning's equation are specified as the downstream boundary condition.

SWAT MODEL DEVELOPMENT

Data Quality and Availability

The basic inputs into the SWAT model included the 30-m USGS National Elevation Dataset (NED), the EPA 1:250,000-scale Land Use Land Cover (LULC) data set, and the USDA NRCS (Natural Resources Conservation Service) State Soil Geographic database (STATSGO). The NED was developed by merging the highest-resolution, best-quality elevation data available across the United States into a seamless raster format. The LULC data set was developed by combining the data obtained from 1970s and 1980s aerial photography surveys with land use maps and surveys. Because there have been negligible changes in the types of land use in the RRB in the past two decades, as indicated by a comparison of the LULC and National Land Cover Dataset that was created by USGS from the 1992 aerial photography surveys, the LULC was an appropriate choice. Soil data contained within the STATSGO database are collected at the USGS 1:250,000-scale in 1- by 2-degree topographic quadrangle units and then merged and distributed as state coverages. STATSGO has a county-level resolution and can be readily used for river basin water resource studies. The NED and LULC data sets were downloaded from the USGS Web site (http://edc.usgs.gove/geodata), and the STATSGO database was downloaded from the USDA NRCS Web site (www.ncgc. nrcs.usda.gov/branch/ssb/products). In addition to these three data sets, the USGS National Hydrography Dataset (NHD) was also used as a model input. The NHD is a comprehensive set of digital spatial data that contains information about surface water features such as lakes, ponds, streams, rivers, springs, and wells. The stream feature provided by NHD was utilized as the reference surface water drainage network to delineate subbasins for each of the USGS 8-digit HUCs for modeling purposes.

The NWS National Climate Data Center (NCDC) collects data on daily precipitation and minimum and maximum temperatures at stations across the RRB. Because the models were calibrated to the 1997 flood and validated against the 1966, 1969, 1975, 1978, and 1979 floods, weather data were utilized for these years. To minimize modeling uncertainties, the stations that had 30% or more values missing between October 1 and May 31 during these years were not used in this modeling effort. In addition to weather data, daily flow data obtained from USGS gauging stations for the aforementioned flood years were used to calibrate and validate the models. Figure C-4 shows the locations of the NWS precipitation and temperature stations and the USGS flow gauging stations that were used in this study. Tables C-2 and 3 list additional information that describes the location and/or location name of the stations.

Calibration and Validation Strategy

The SWAT models were calibrated to the 1997 spring flood event using daily flow data observed from January 1 to May 31, 1997. In some instances, additional validation of the models was conducted using flow data recorded from January 1 to May 31 of 1966, 1969, 1975, 1978, and 1979. The calibration of the models was implemented to adjust three snowmelt-sensitive parameters (variables SMFMX, TIMP, and SMTMP), three additional watershed-level parameters, namely the surface runoff lag coefficient (variable SURLAG) and the Muskingum translation coefficients for normal flow (variable MSK_CO1) and for low flow (variable MSK_CO2), and three HRU-level parameters, namely the SCS curve number for soil moisture

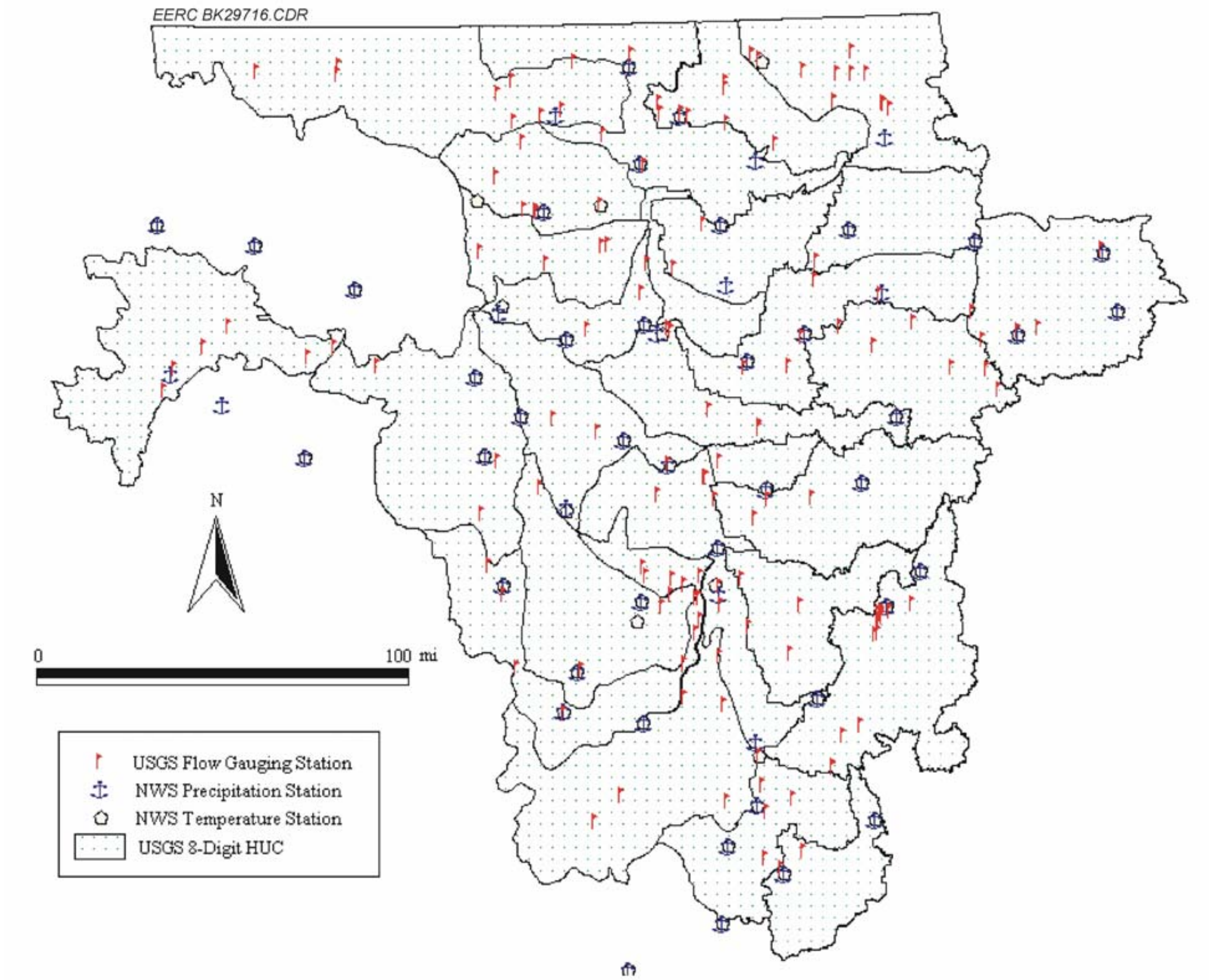


Figure C-4. Map showing the locations of the weather stations and flow-gauging stations that were used in this study.

condition II (variable CN2), the threshold depth of water in the shallow aquifer required for return flow to occur (variable GWQMN), and the soil evaporation compensation factor (variable ESCO). In addition, in some watersheds, three main channel-related parameters, namely, average slope (variable CH_S2), length (variable CH_L2), and effective hydraulic conductivity (variable CH_K2), and one groundwater-related parameter, namely, baseflow alpha factor (variable ALPHA_BF), were also adjusted. In the few cases where flow data were not available for a particular watershed, the SWAT models were set up based on scientific judgment, spot values observed by local engineers, and/or calibrated model parameters in the adjacent watersheds. Table C-4 summarizes the setup of the SWAT models.

Table C-2. Location of Weather Stations Whose Data Were Used in This Study

COOP ID [1]	X (m) [2]	Y (m) [2]	Latitude (degree) [3]	Longitude (degree) [3]	Elevation (m) [4]	Parameter [5]
210018	688243.0000	5241291.0000	47.3000	-96.5100	150.00	P, T
210050	723964.4897	5353834.8508	48.3000	-95.9800	348.10	P, T
210195	671238.3104	5329754.8350	48.3300	-96.7300	264.90	T
210252	668249.3397	5355250.7371	45.6100	-96.8300	265.20	P, T
211063	669208.9776	5052789.9167	48.9600	-96.4500	301.80	P, T
211303	686660.3067	5425924.1108	47.8000	-96.6000	310.90	P
211891	679720.6359	5296641.8282	46.8300	-95.8500	267.70	P, T
212142	740239.0000	5190873.0000	46.0000	-95.9600	151.00	P, T
212476	735397.6073	5098323.7836	47.5600	-95.7500	405.40	P, T
212916	744485.6858	5272299.0043	47.0800	-96.8000	399.30	P, T
213104	667008.6801	5216184.2882	48.7600	-96.9500	269.70	P, T
213455	650661.9192	5402584.8182	47.9300	-94.4500	246.90	P, T
213756	738469.3082	5326593.8255	47.3100	-95.9600	350.50	T
214213	683649.9902	5383542.4572	47.9000	-96.2600	325.20	T
214233	839842.7733	5318328.1180	47.8600	-95.0300	423.70	P, T
215012	729776.0000	5243878.0000	46.4800	-96.2600	118.00	P, T
216787	704784.9849	5308601.3739	46.9600	-95.6500	327.70	P, T
216795	796930.2784	5308154.9370	48.2300	-95.2500	371.90	P, T
217149	710324.8156	5150810.8827	48.1600	-94.5100	376.70	P, T
218191	754873.7493	5205949.3706	45.8000	-96.4800	118.00	P, T
218254	778474.0569	5348446.6926	48.4462	-98.1395	362.70	P, T
218656	739365.7717	5393428.9796	47.4462	-99.1396	362.70	T
218700	833869.8987	5343620.5311	46.8800	-97.2300	365.80	P, T
218907	695835.4783	5074697.1468	46.8000	-97.2600	310.30	P, T
320022	563636.7400	5366031.2300	47.2300	-97.6500	473.70	P
321360	489472.9000	5254538.8500	47.4500	-98.1100	483.00	P, T
321408	634869.0200	5193131.4300	48.1020	-98.8501	285.00	P, T
321435	597902.9100	5403133.5100	48.5800	-97.1800	271.00	T
321477	632780.1400	5184190.7400	46.6100	-97.6000	294.00	P
321686	602196.0000	5231389.0000	46.9352	-96.8169	359.70	P, T
321766	567094.4300	5255338.1400	48.4166	-97.4167	421.00	P, T
322158	511163.0800	5327429.6000	47.9500	-97.1800	446.20	P, T
322312	634236.5658	5382148.1082	47.9100	-97.0800	243.80	P, T
322695	607210.5000	5162559.9000	46.0687	-96.6171	351.00	P, T
322859	666170.6500	5200061.1900	47.4000	-97.0600	274.00	P, T
322949	453899.8700	5277576.6200	47.9000	-97.6300	493.80	T
323594	617156.6800	5363600.9100	48.2756	-99.4345	252.10	P
323616	635896.8999	5312127.0743	46.4519	-97.6837	255.70	P, T
323621	643474.1121	5307862.5778	47.5000	-97.3100	253.00	P, T
323908	684286.0000	5104220.0000	46.4020	-97.2334	326.10	P, T
324013	431200.9000	5290789.4600	47.7600	-98.1600	487.70	T
324203	646388.0000	5251222.0000	48.4000	-97.7500	275.00	P, T
325013	602395.0000	5305875.0000	48.9568	-97.2325	345.00	P, T
325078	467761.6200	5346800.9400	48.0300	-98.0000	466.00	P, T
325220	601095.9700	5144886.3000	48.3517	-100.0067	337.00	P, T
325660	627282.0755	5261895.1789	47.6015	-97.9017	288.30	P, T
325754	635800.0000	5140015.0000	46.9500	-98.0166	327.70	P, T
325764	562952.0000	5289749.0000	46.2600	-96.6000	447.00	P, T
326857	592523.3700	5361295.9500	45.9173	-96.7845	295.70	P, T
326947	629393.3100	5423941.9000	45.4354	-97.3504	241.00	P, T
327027	574554.0000	5319899.0000	47.3000	-96.5100	466.00	P, T
327704	425416.1500	5355663.9400	48.3000	-95.9800	472.00	P, T
327986	582558.9000	5272371.5000	48.3300	-96.7300	464.80	P, T
328937	574835.3300	5199858.6300	45.6100	-96.8300	369.00	P, T
329100	684968.0000	5125517.0000	48.9600	-96.4500	291.40	P, T
398652	671808.1600	5087028.2400	47.8000	-96.6000	329.20	P, T
398980	629029.0000	5032422.0000	46.8300	-95.8500	557.80	P, T

[1] The 6-digit NWS Cooperative Station Identifier (COOP ID) for the station.

[2] NAD 1927 UTM Zone 14N.

[3] NAD 1983.

[4] NGVD 1929 above sea level.

[5] P signifies precipitation, and T signifies minimum and maximum temperatures.

Table C-3. USGS Flow-Gauging Stations That Were Used to Set Up the SWAT and HEC–RAS Models in This Study

USGS ID	Station Name	USGS ID	Station Name
05030000	Otter Tail River near Detroit Lakes, MN	05084500	Forest River near Minto, ND
05030150	Otter Tail River near Perham, MN	05085000	Forest River at Minto, ND
05030500	Otter Tail River near Elizabeth, MN	05085900	Snake River above Alvarado, MN
05033900	Pelican River at Detroit Lakes, MN	05087500	Middle River at Argyle, MN
05034100	Pelican River at Detroit Lakes outlet near Detroit Lakes, MN	05088000	South Branch Park River near Park River, ND
05035100	Long Lake outlet near Detroit Lakes, MN	05088500	Homme Reservoir near Park River, ND
05035200	West Branch County ditch #14 near Detroit Lakes, MN	05089000	South Branch Park River below Homme Dam, ND
05035300	East Branch County ditch #14 near Detroit Lakes, MN	05089100	Middle Branch Park River near Union, ND
05035500	St. Clair Lake outlet near Detroit Lakes, MN	05089500	Cart Creek at Mountain, ND
05035600	Pelican River at Muskrat Lake outlet near Detroit Lakes, MN	05090000	Park River at Grafton, ND
05037100	Pelican River at Sallie Lake outlet near Detroit Lakes, MN	05092000	Red River of the North at Drayton, ND
05039100	Pelican River at Lake Melissa outlet near Detroit Lakes, MN	05092200	Pembina County Drain 20 near Glasston, ND
05040000	Pelican River near Detroit Lakes, MN	05092500	Middle Branch Two Rivers near Hallock, MN
05040500	Pelican River near Fergus Falls, MN	05093000	South Branch Two Rivers at Pelan, MN
05045950	Orwell Lake near Fergus Falls, MN	05094000	South Branch Two Rivers at Lake Bronson, MN
05046000	Otter Tail River below Orwell Dam near Fergus Falls, MN	05095000	Two Rivers at Hallock, MN
05047500	Mustinka Dam above the west branch of Mustinka near Charlesville, MN	05095500	Two Rivers below Hallock, MN
05048000	Mustinka Dam below the west branch of Mustinka near Charlesville, MN	05096000	North Branch Two Rivers near Lancaster, MN
05048500	West branch of Mustinka River below Mustinka Dam near Charlesville, MN	05096500	State Ditch #85 near Lancaster, MN
05049000	Mustinka River above Wheaton, MN	05097500	North Branch Two Rivers near Northcote, MN
05050000	Bois de Sioux River near White Rock, SD	05098700	Hidden Island Coulee near Hansboro, ND
05050500	Bois de Sioux River near Fairmount, ND	05098800	Cypress Creek near Sarles, ND
05051000	Rabbit River at Campbell, MN	05098820	Cypress Creek above International Boundary near Sarles, ND
05051300	Bois de Sioux River near Doran, MN	05099400	Little South Pembina River near Walhalla, ND
05051500	Red River of the North at Wahpeton, ND	05099600	Pembina River at Walhalla, ND

Continued . . .

Table C-3. U.S. Geological Survey Flow-Gauging Stations That Were Used to Set Up the SWAT and HEC–RAS Models in this Study (continued)

USGS ID	Station Name	USGS ID	Station Name
05051522	Red River of the North at Hickson, ND	05100000	Pembina River at Neche, ND
05051600	Wild Rice River near Rutland, ND	05100500	Herzog Creek near Concrete, ND
05051700	Wild Rice River near Cayuga, ND	05101000	Tongue River at Akra, ND
05052100	Richland County Drain #65 near Great Bend, ND	05101500	Tongue River at Cavalier, ND
05053000	Wild Rice River near Abercrombie, ND	05102500	Red River of the North at Emerson, MB
05054000	Red River of the North at Fargo, ND	05103000	Roseau River near Malung, MN
05054020	Red River of the North below Fargo, ND	05104000	South Fork Roseau River near Malung, MN
05054500	Sheyenne River above Harvey, ND	05104500	Roseau River below South Fork near Malung, MN
05055000	Sheyenne River near Harvey, ND	05106500	Roseau River at Roseau Lake, MN
05055100	North Fork of Sheyenne River near Wellsburg ND	05107000	Pine Creek near Pine Creek, MN
05055200	Big Coulee near Maddock, ND	05107500	Roseau River at Ross, MN
05055500	Sheyenne River at Sheyenne, ND	05108000	Roseau River near Badger, MN
05055520	Big Coulee near Ft. Totten, ND	05109000	Badger Creek near Badger, MN
05056000	Sheyenne River near Warwick, ND	05109500	Roseau River near Haug, MN
05057000	Sheyenne River near Cooperstown, ND	05112000	Roseau River below State Ditch 51 near Caribou, MN
05057200	Baldhill Creek near Dazey, ND	05112500	Roseau River at International Boundary near Caribou, MN
05058000	Sheyenne River below Baldhill Dam, ND	05084500	Forest River near Minto, ND
05058500	Sheyenne River at Valley City, ND	05085000	Forest River at Minto, ND
05058600	Sheyenne River near Kathryn, ND	05085900	Snake River above Alvarado, MN
05058700	Sheyenne River at Lisbon, ND	05087500	Middle River at Argyle, MN
05059000	Sheyenne River near Kindred, ND	05088000	South Branch Park River near Park River, ND
05059300	Sheyenne River above Sheyenne River Diversion near Horace, ND	05088500	Homme Reservoir near Park River, ND
05059310	Sheyenne River Diversion near Horace, ND	05089000	South Branch Park River below Homme Dam, ND
05059400	Sheyenne River near Horace, ND	05089100	Middle Branch Park River near Union, ND
05059480	Sheyenne River Diversion at West Fargo, ND	05089500	Cart Creek at Mountain, ND
05059500	Sheyenne River at West Fargo, ND	05090000	Park River at Grafton, ND
05059600	Maple River near Hope, ND		

Table C-4. Setup of the SWAT Models

State	Modeling Domain	Calibration	Validation	Method and/or Data Used
MN	HUC 09020101	No	No	Judgment; A spot 1997 peak of 6000 cfs was provided by a consulting engineer
	HUC 09020102	No	No	Judgment; A spot 1997 peak of 8800 cfs at USGS gauging station
	HUC 09020103	Yes	Yes	Daily stream flows observed at USGS gauging stations 05030500 and 05046000
	HUC 09020104	Yes	Yes	Daily stream flows at two USGS gauging stations 05051522 and 05054000; Validation for 1979 and 1978 only
	HUC 0920106	Yes	Yes	Daily stream flows at USGS gauging station 05061500; A spot 1997 peak flow of 340 cfs at USGS gauging station 05061200
	HUC 09020107	Yes	Yes	Daily stream flows at USGS gauging station 05067500
	HUC 09020108	Yes	Yes	Daily stream flows at USGS gauging stations 05062500 and 05064000
	HUC 09020301	Yes	Yes	Daily stream flows at USGS gauging station 05069000
	HUC 09020302	No	No	Judgment
	HUC09020303	Yes	Yes	Daily stream flows at USGS gauging stations 05075000 and 05079000
	HUC 09020304	Yes	Yes	Daily stream flows at USGS gauging station 05076000
	HUC 09020305	Yes	Yes	Daily stream flows at USGS gauging stations 05078000, 05078230, and 05078500
	HUC 09020306	No	No	Judgment
	HUC 09020309	Yes	Yes	Daily stream flows at USGS gauging station 05087500
	HUC 09020311	No	No	Judgment
	HUC 09020312	Yes	Yes	Daily stream flows at USGS gauging station 05094000
	HUC 09020314	Yes	Yes	Daily stream flows at USGS gauging station 05112000
ND	HUC 09020101	Yes	No	Daily stream flows at the outlet of the Big Slough River obtained from USACE
	HUC 09020105	Yes	No	Daily stream flows at USGS gauging stations 05051600 and 05053000
	HUC 09020107	No	Yes	Daily stream flows at USGS gauging stations 05062200 for the 1978, 1975, and 1969 floods
	HUC 09020109	Yes	Yes	Daily stream flows at USGS gauging stations 05064900 and 05066500
	HUC 09020202	Yes	No	Daily stream flows at USGS gauging station 05054500
	HUC 09020203	Yes	No	Daily stream flows at USGS gauging stations 05056000 and 05057000
	HUC 09020204	Yes	No	Daily stream flows at USGS gauging stations 05058700, 05059000 and 05059500
	HUC 09020205	Yes	No	Daily stream flows at USGS gauging stations 05059700 and 05060100
	HUC 09020301	No	No	Judgment
	HUC 09020307	Yes	No	Daily stream flows at USGS gauging station 05082625
	HUC 09020308	Yes	No	Daily stream flows at USGS gauging stations 05084000 and 05085000
	HUC 09020310	Yes	No	Daily stream flows at USGS gauging station 05090000
	HUC 09020311	No	No	Judgment
	HUC 09020313	Yes	No	Daily stream flows at USGS gauging stations 05100000 and 05101000

Measures of Model Performance

One of the key visual measures of model performance was how well simulated flow hydrographs matched the shape, volume, and peak of observed hydrographs for given locations within a watershed. Besides visualization, three statistics, namely, the Nash–Sutcliffe coefficient, volume deviation, and error function, were also used to determine model performance in this study. These statistics can be applied for daily, monthly, seasonal, and annual evaluation time steps. The Nash–Sutcliffe coefficient measures the overall fit of the modeled hydrograph to that of an observed flow hydrograph, but it may be an inappropriate measure for use in simulating the volume, which is computed by integrating the flow hydrograph over the evaluation period and for predicting the peak(s) of the hydrograph. In addition to the Nash–Sutcliffe coefficient, two extra statistics, namely, deviation of volume and error function, are generally employed to test whether the volume and peak(s) of an observed hydrograph are appropriately predicted. Therefore, in addition to the Nash–Sutcliffe coefficient, the deviation of volume was employed to test whether the volume of an observed hydrograph is appropriately predicted.

The Nash–Sutcliffe coefficient (E_j^2) is computed as:

$$E_j^2 = 1 - \frac{\sum_{i=1}^{n_j} (Q_{\mathrm{obs}i}^j - Q_{\mathrm{sim}i}^j)^2}{\sum_{i=1}^{n_j} (Q_{\mathrm{obs}i}^j - Q_{\mathrm{mean}}^j)^2} \qquad \text{[Eq. 47]}$$

where $Q_{\mathrm{sim}i}^j$ and $Q_{\mathrm{obs}i}^j$ are the simulated and observed stream flows, respectively, on the ith time step for station j, and Q_{mean}^j is the average of $Q_{\mathrm{obs}i}^j$ across the n_j evaluation time steps.

The deviation of volume (D_{vj}) is computed as:

$$D_{vj} = \frac{\sum_{i=1}^{n_j} Q_{\mathrm{sim}i}^j - \sum_{i=1}^{n_j} Q_{\mathrm{obs}i}^j}{\sum_{i=1}^{n_j} Q_{\mathrm{obs}i}^j} \times 100\% \qquad \text{[Eq. 48]}$$

The peak flow-weighted error function (E_{RRj}) is computed as:

$$E_{\mathrm{RRj}} = \frac{\sum_{k=1}^{m_j} Q_{\mathrm{obs}}^{\mathrm{jkp}} \left[\left(\frac{Q_{\mathrm{obs}}^{\mathrm{jkp}} - Q_{\mathrm{sim}}^{\mathrm{jkp}}}{Q_{\mathrm{obs}}^{\mathrm{jkp}}} \right)^2 + \left(\frac{T_{\mathrm{obs}}^{\mathrm{jkp}} - T_{\mathrm{sim}}^{\mathrm{jkp}}}{T_c} \right)^2 \right]^{\frac{1}{2}}}{\sum_{k=1}^{m_j} Q_{\mathrm{obs}}^{\mathrm{jkp}}} \times 100\% \qquad \text{[Eq. 49]}$$

where m_j is the number of evaluation years at station j, Q_{sim}^{jkp} and Q_{obs}^{jkp} are the simulated and observed peak discharges, respectively, for evaluation year k at station j, T_{sim}^{jkp} and T_{obs}^{jkp} are the timings of the simulated and observed peaks, respectively, for evaluation year k at station j, and T_c is the SWAT-estimated time of concentration for the watershed.

The value of E_j^2 can range from $-\infty$ to 1.0, with higher values indicating a better overall fit and 1.0 indicating a perfect fit. A negative E_j^2 indicates that for station j the simulated stream flows are less reliable than if one had used the average of the observed stream flows, while a positive value indicates that they are more reliable than using this average. The value of D_{vj} can range from very small negative to very large positive values, with values close to zero indicating a better simulation and zero indicating an exact prediction of the observed volume. In contrast with E_j^2, E_{RRj} can range from 0.0 to $+\infty$, with lower values indicating a better simulation of the observed peak and 0.0 indicating that both the magnitude and timing of the observed peak can be exactly predicted by the model.

SWAT Model Development for the Minnesota Watersheds

As shown in Table C-4, the Minnesota jurisdiction in the RRB was divided into 17 modeling domains, leading to 17 SWAT models. These domains coincide with the USGS 8-digit HUCs that are solely located in the jurisdiction (e.g., HUC 09020106 and 09020108) but consist of portions of the HUCs that are located both in the Minnesota and North Dakota jurisdictions (e.g., HUC 09020101 and 09020107). Table C-5 summarizes the measuring statistics of the model performances.

For the calibration year of 1997, the E_j^2 values for most evaluation stations are greater than 0.36, indicating that the SWAT models were calibrated to have a satisfactory simulation performance. Because these values are comparable to, or greater than, that reported in the literature, these models are considered to be sufficiently calibrated, i.e., given the available data, further improvement of the model performance would be very limited. The poor model performance at station USGS 05078230 might be attributed to the fact that there was insufficient data on the large amount of marshes/wetlands (e.g., storage volumes and geographic locations) located in HUC 09020305 (the Clearwater River Watershed). The E_j^2 value at USGS gauging station 05067500 is slightly lower than 0.36 because the data on the water diverted from HUC 09020108 (the Eastern Wild Rice River watershed) to HUC 09020107 (the Marsh River Watershed) were unavailable and was assumed to be a constant that was determined based on the geometry of the diversion channel, leading to an 18.8% overestimation of the total stream flow for the calibration period.

The models performed well at reproducing the total runoff volumes observed at most of the stations. The large prediction errors for HUC 09020103 (the Otter Tail River watershed), HUC 09020104 (the Upper Red River watershed), HUC 09020305, and HUC 09020314 (the Roseau River Watershed) might be caused by the inaccurate data on marshes/wetlands, whereas the large prediction error at USGS gauging station 05067500 might be because there were no data on the water diverted from HUC 09020108.

The low E_{RRj} values indicate that the models can accurately predict both the magnitude and timing of the peaks observed at most of the stations. Again, the poor prediction of the peak at USGS gauging station 05112000 probably resulted from the insufficient data on marsh and/or wetland locations.

For the validation years, the three statistics exhibit large variations (Table C-5) across the evaluation stations. This indicates that the models are more robust for some historical flood events than the others. Generally the models have a better simulation performance for the flood events that occurred in 1970s than the ones that occurred in 1960s. In general, the variation in model performance for the validation years is not surprising given the likely differences in the landscape between the validation years (1960s and 1970s) and the calibration year (1997). Nevertheless, for most stations, the values of the statistics are comparable with that reported in the literature. Hence, the models are considered to be reliable for predicting stream flows and peaks of large historical flood events.

To further evaluate the model performance, Figures C-5–C-8 illustrate the predicted versus observed flow hydrographs at selected stations for the calibration year of 1997. These stations were selected because the models had noticeably different simulation performances as indicated by the E_j^2 values ranging from 0.27 to 0.86. Visual inspection revealed that for the stations with a high E_j^2 value, the models successfully reproduced both the peaks and total stream flow volumes. For the stations with a low E_j^2 value, the models successfully reproduced the peaks but tended to have a large prediction error of the total stream flow volumes. A close examination of the flow hydrographs at the other evaluation stations with low E_j^2 values indicated a similar prediction pattern. Again, the lack of data for characterizing the marshes and wetlands might be one reason for the inaccurate predictions of total stream volumes. Another reason might be that the model-generated weather data to fill missing values for daily precipitation and minimum and maximum temperatures could not accurately represent the weather conditions that actually occurred.

Nevertheless, the models were judged to be accurate enough for evaluating the effects of Waffle storage on mitigating 1997-type flooding, which was the focus of the study.

SWAT Models for the North Dakota Watersheds

As shown in Table C-4, the North Dakota jurisdiction in the RRB was divided into 14 modeling domains, leading to 14 SWAT models. These domains coincide with the USGS 8-digit HUCs that are solely located in the jurisdiction (e.g., HUC 09020109 and 09020308) but consist of portions of the HUCs that are located both in the Minnesota and North Dakota jurisdictions (e.g., HUC 09020101 and 09020107). Table C-6 summarizes the measuring statistics of the model performances.

Table C-5. Nash–Sutcliffe Coefficient (E_j^2), Deviation of Volume (D_{vj}), and Error Function (E_{RRj}) of the Minnesota SWAT Models

Modeling Domain	Calibration Parameters	Calibration			Validation		
		E_j^2	D_{vj} (%)	E_{RRj} (%)	E_j^2	D_{vj} (%)	E_{RRj} (%)
HUC 09020101	SMFMX (6.9), TIMP (0.3), SMTMP (1.5), SURLAG (5), MSK_CO1 (0.6), MSK_CO2 (0.6), ESCO (0.95), GWQMN (0), CN2 (-5%)	–	–	–	–	–	–
HUC 09020102	SMFMX (6.9), TIMP (0.3), SMTMP (1.5), SURLAG (5), MSK_CO1 (1.7), MSK_CO2 (1.7), ESCO (0.95), GWQMN (0), CN2 (-5%)	–	–	–	–	–	–
HUC 09020103	SMFMX (5.43), TIMP (0.88), SMTMP (0.278), SURLAG (24), MSK_CO1 (15.046), MSK_CO2 (15.161), ESCO (0.95), GWQMN (0), CN2 (-10%)	0.47 ~ 0.67	23 ~ 28	13.2 ~ 20.3	−0.56 ~ 0.73	3 ~ 57	22.5 ~ 53.1
HUC 09020104	SMFMX (7.5), TIMP (0.6), SMTMP (1.5), SURLAG (2.5), MSK_CO1 (1.2), MSK_CO2 (1.2), ESCO (0.95), GWQMN (0), CN2 (-10%)	0.47 ~ 0.61	28 ~ 37	10.4 ~ 12.5	0.61 ~ 0.92	0.8 ~ 53	1.6 ~ 45.9
HUC 0920106[1]	SMFMX (6.9), TIMP (0.1 ~ 0.15), SMTMP (1.0 ~ 1.5), SURLAG (0.3 ~ 0.82), MSK_CO1 (0.35 ~ 1.2), MSK_CO2 (0.35~1.2), ESCO (0.95), GWQMN (0), CN2 (-6.4 ~ +7.0)	0.76	−1.9	1.1	−1.23 ~ 0.90	−179.0 ~ 0.4	1.1 ~ 114.4
HUC 09020107	SMFMX (6.9), TIMP (0.1), SMTMP (1.5), SURLAG (3.5), MSK_CO1 (1.2), MSK_CO2 (1.2), ESCO (0.95), GWQMN (0), CN2 (+8.0)	0.27	18.8	7.7	0.54 ~ 0.89	−9.8 ~ 2.5	2.9 ~ 15.4
HUC 09020108	SMFMX (10), TIMP (0.6), SMTMP (3.5), SURLAG (1.5), MSK_CO1 (1.2), MSK_CO2 (1.2), ESCO (0.95), GWQMN (0), CN2 (+3.0)	0.61 ~ 0.86	−0.1 ~ 2.3	2.2 ~ 7.0	0.11 ~ 0.79	−21.4 ~ 16.6	3.3 ~ 76.4
HUC 09020301	SMFMX (7), TIMP (0.9), SMTMP (0.5), SURLAG (15), MSK_CO1 (2.8), MSK_CO2 (2.8), ESCO (0.95), GWQMN (0), CN2 (default)	0.54	4.8	2.9	0.59 ~ 0.90	−21.5 ~ 1.1	1.0 ~ 7.7
HUC 09020302	SMFMX (6.9), TIMP (0.3), SMTMP (1.2), SURLAG (12), MSK_CO1 (1.2), MSK_CO2 (1.2), ESCO (0.95), GWQMN (0), CN2 (default)	–	–	–	–	–	–

Continued . . .

Table C-5. Nash-Sutcliffe Coefficient (E_j^2), Deviation of Volume (D_{vj}), and Error Function (E_{RRj}) of the Minnesota SWAT Models (continued)

Modeling	Calibration Parameters	Calibration			Validation		
		E_j^2	D_{vj} (%)	E_{RRj} (%)	E_j^2	D_{vj} (%)	E_{RRj} (%)
HUC09020303	SMFMX (7.9), TIMP (0.3), SMTMP (2.5), SURLAG (1), MSK_CO1 (3.9), MSK_CO2 (3.9), ESCO (0.95), GWQMN (0), CN2 (default), CH_S2 (+0.006), CH_L2 (-20%)	0.76	−5.7 ~ -1.7	4.6 ~ 10.6	−0.14 ~ 0.89	−22.2 ~ 23.0	1.4 ~ 53.9
HUC 09020304	SMFMX (7.9), TIMP (0.3), SMTMP (2.5), SURLAG (1), MSK_CO1 (3.9), MSK_CO2 (3.9), ESCO (0.95), GWQMN (0), CN2 (default), CH_S2 (+0.004), CH_L2 (-70%)	0.86	−3.5	15.4	0.54 ~ 0.89	−3.9 ~ 38.5	5.3 ~ 68.6
HUC 09020305	SMFMX (7.9), TIMP (0.3), SMTMP (2.5), SURLAG (1), MSK_CO1 (3.9), MSK_CO2 (3.9), ESCO (0.95), GWQMN (0), CN2 (default), CH_S2 (+0.002), CH_K2 (+0.02), ALPHA_BF (-0.02)	−0.04 ~ 0.66	-41.7 ~ -12.6	18.3 ~ 26.1	−1.66 ~ 0.86	−48.3 ~ 28.7	0.1 ~ 49.7
HUC 09020306	SMFMX (7.0), TIMP (0.4), SMTMP (4.0), SURLAG (1), MSK_CO1 (3.9), MSK_CO2 (3.9), ESCO (0.95), GWQMN (0), CN2 (default)	–	–	–	–	–	–
HUC 09020309	SMFMX (7.0), TIMP (0.15), SMTMP (3.0), SURLAG (2), MSK_CO1 (1.2), MSK_CO2 (1.2), ESCO (0.95), GWQMN (0), CN2 (default)	0.57	0.2	2.8	0.27 ~ 0.88	−5.1 ~ 23.4	1.9 ~ 23.4
HUC 09020311	SMFMX (7.0), TIMP (0.15), SMTMP (3.0), SURLAG (2), MSK_CO1 (1.2), MSK_CO2 (1.2), ESCO (0.95), GWQMN (0), CN2 (default)	–	–	–	–	–	–
HUC 09020312	SMFMX (7.5), TIMP (0.35), SMTMP (1.0), SURLAG (4), MSK_CO1 (3.5), MSK_CO2 (3.5), ESCO (0.95), GWQMN (0), CN2 (default)	0.59	16.9	5.6	0.40 ~ 0.86	1.8 ~ 45.1	1.1 ~ 60.4
HUC 09020314	SMFMX (6.9), TIMP (0.3), SMTMP (1.5), SURLAG (1.4), MSK_CO1 (1.2), MSK_CO2 (1.2), ESCO (0.95), GWQMN (0), CN2 (default)	0.77	−22.4	60.7	−0.72 ~ 0.75	−68.6 ~ 43.1	52.6 ~ 119.3

---

[1] The watershed was modeled using two separate SWAT models: one for the drainage area upstream of Sabin (USGS 05061500) and another for the remaining drainage area.

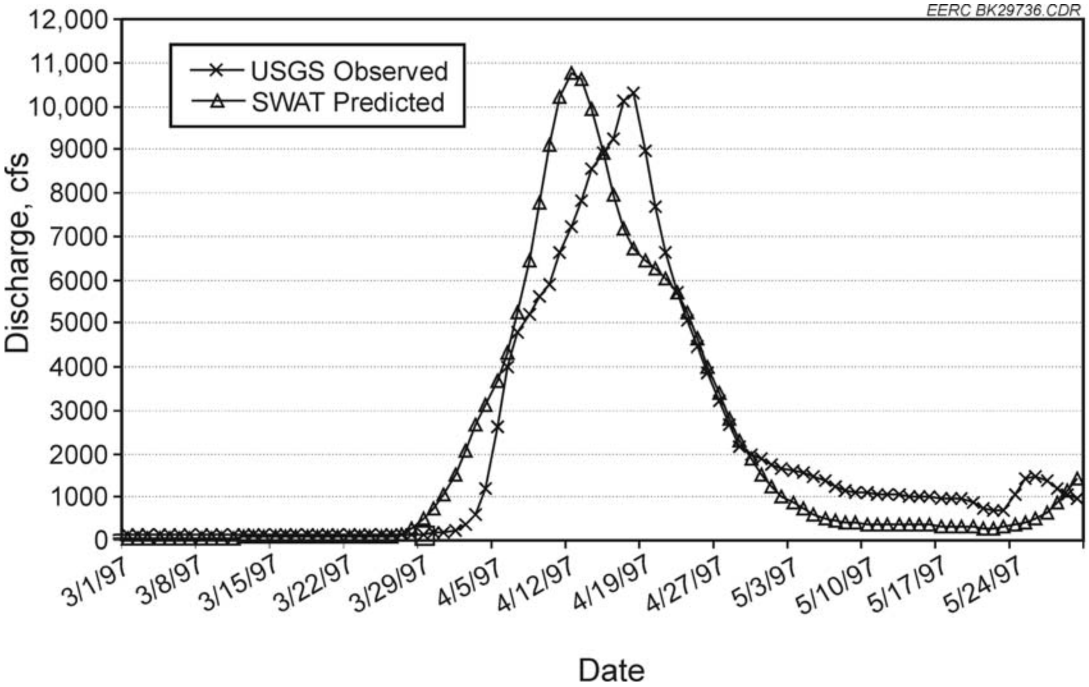


Figure C-5. Model-predicted vs. observed stream flow hydrographs at Hendrum (USGS 05064000) in the Eastern Wild Rice River Watershed (HUC 09020108). The Nash–Sutcliffe coefficient $E_j^2 = 0.86$.

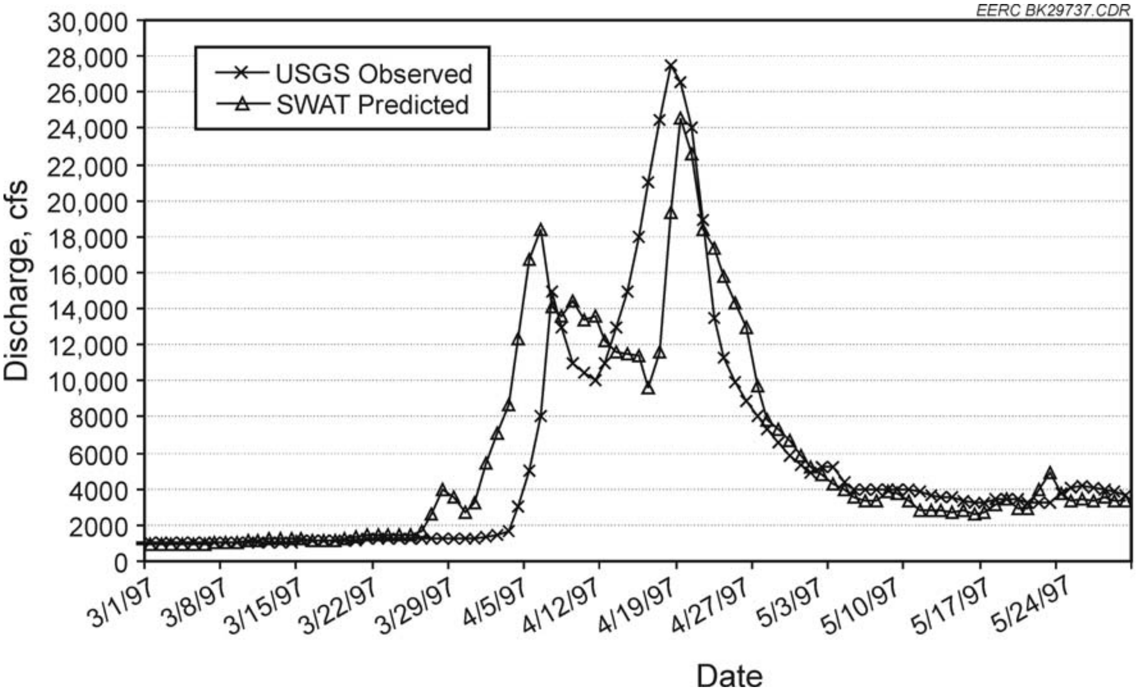


Figure C-6. Model-predicted vs. observed stream flow hydrographs at Crookston (USGS 05079000) in the Red Lake River Watershed (HUC 09020303). The Nash–Sutcliffe coefficient $E_j^2 = 0.76$.

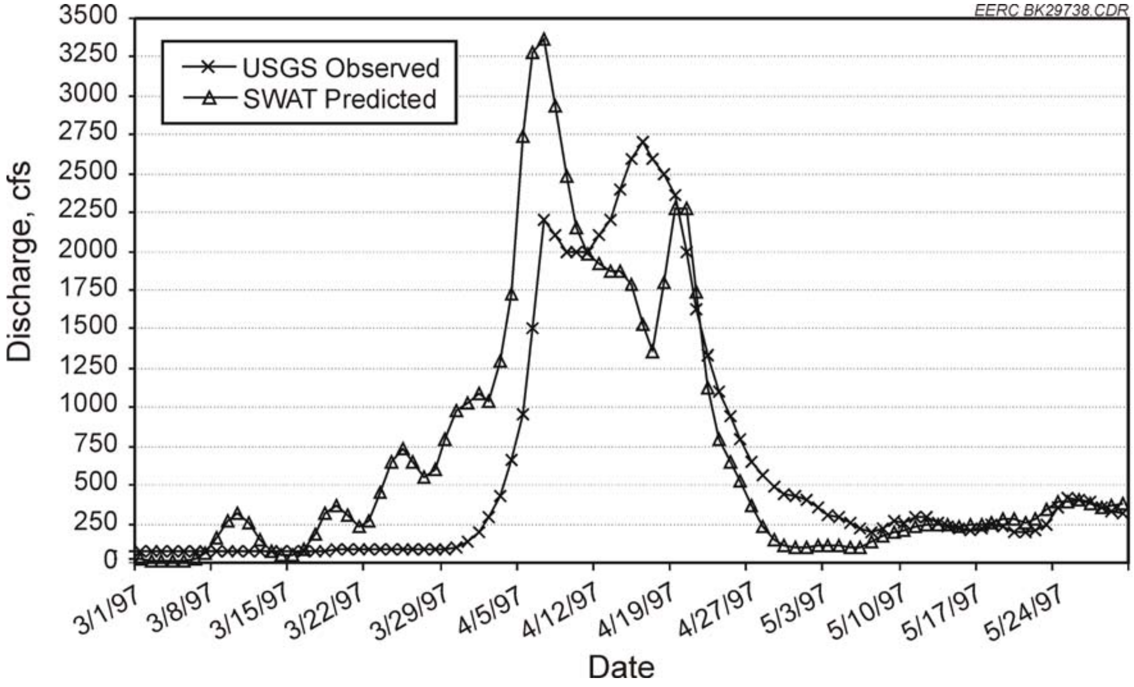


Figure C-7. The model-predicted vs. observed stream flow hydrographs at Plummer (USGS 05078000) in the Clearwater River Watershed (HUC 09020305). The Nash–Sutcliffe coefficient $E_j^2 = 0.66$.

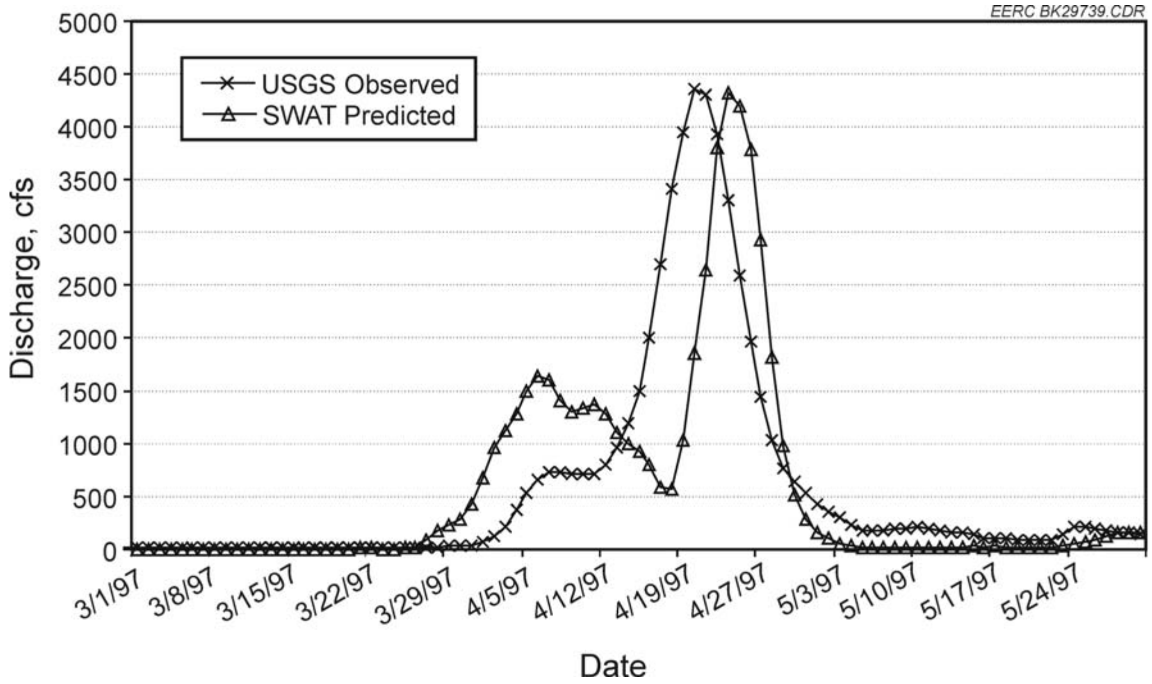


Figure C-8. The model-predicted vs. observed stream flow hydrographs at Climax (USGS 05069000) in the Sandhill River Watershed (HUC 09020301). The Nash–Sutcliffe coefficient $E_j^2 = 0.54$.

For the calibration year of 1997, the E_j^2 values for most evaluation stations are greater than 0.55, indicating that the SWAT models were calibrated to have a satisfactory simulation performance. Because these values are comparable with or greater than that reported in the literature, these models are considered to be sufficiently calibrated, i.e., given the available data, further improvement of the model performance would be very limited. The poor model performance at station USGS 05056000 may be a result of insufficient data on the large number of marshes/wetlands (e.g., storage volumes and geographic locations) located in HUC 09020203 (the Middle Sheyenne River Watershed). The model noticeably underestimated the total stream flows for this modeling domain. The low E_{RRj} values indicate that the models can accurately predict both the magnitudes and timings of the peaks observed at most of the stations. The poor prediction of peaks at some stations (e.g., USGS gauging stations 05056000 and 05057000 in the Middle Sheyenne River Watershed) is, again, probably a result of insufficient data on marsh and wetland locations and because of SWAT's inability to handle ice jams that occur in river channels (e.g., USGS gauging stations 05059700 and 05060100 in the Maple River Watershed).

Two of the North Dakota SWAT models, corresponding to HUCs 09020107 (Elm River) and 09020109 (Goose River), were validated in accordance with the other historical floods (Table C-6). The validation indicates that the models are more robust for some historical flood events than for others. Generally, as expected, the models have a better simulation performance for the flood events that occurred in the 1970s than the ones that occurred in the 1960s. Compared with the 1970s, the watershed conditions in the 1960s were likely more different from the ones used to set up and calibrate the models. Nevertheless, for most stations, the values of the statistics are comparable with that reported in the literature. Hence, the models are considered to be reliable for predicting stream flows and peaks of the typical historical flood events.

To further evaluate the model performance, Figures C-9–11 illustrate the predicted versus observed flow hydrographs at selected stations for the calibration year of 1997. These stations were selected because the models had noticeably different simulation performances as indicated by the E_j^2 values ranging from −0.01 to 0.91. Visual inspection revealed that for the stations with a high E_j^2 value, the models successfully reproduced both the peaks and total stream flow volumes. For the stations with a low E_j^2 value, the models successfully reproduced the peaks but tended to have a large prediction error of the total stream flow volumes. A close examination of the flow hydrographs at the other evaluation stations with low E_j^2 values indicated a similar prediction pattern. Again, the insufficiency of the data for characterizing marshes and wetlands might be one reason for the inaccurate predictions of the total stream volumes. Another reason might be that the model-generated weather data used to fill the missing values for daily precipitation and minimum and maximum temperatures could not accurately represent the weather conditions that actually occurred. Nevertheless, the models were judged to be accurate enough for evaluating the effects of Waffle storage on reducing 1997-type floods, which was the focus of the study.

Table C-6. Nash–Sutcliffe Coefficient (E_j^2), Deviation of Volume (D_{vj}), and Error Function (E_{RRj}) of the North Dakota SWAT Models

Modeling Domain	Calibration Parameters	Calibration			Validation		
		E_j^2	D_{vj} (%)	E_{RRj} (%)	E_j^2	D_{vj} (%)	E_{RRj} (%)
HUC 09020101[1]	SMFMX (8), TIMP (0.4 ~ 0.95), SMTMP (0), SURLAG (1.3 ~ 4), MSK_CO1 (0.8 ~ 1.2), MSK_CO2 (1.2 ~ 3.0), ESCO (0.95), GWQMN (0), CN2 (+5%)	0.77	1.8	17.2	–	–	–
HUC 09020105	SMFMX (6.0), TIMP (0.15), SMTMP (3), SURLAG (2), MSK_CO1 (1), MSK_CO2 (1), ESCO (0.95), GWQMN (0), CN2 (default)	0.55 ~ 0.64	−5.7 ~ 25.9	7.1 ~ 37.4	–	–	–
HUC 09020107	SMFMX (10.0), TIMP (0.4), SMTMP (3.5), SURLAG (1.5), MSK_CO1 (0.2), MSK_CO2 (0.2), ESCO (0.95), GWQMN (0), CN2 (default)	–	–	–	0.50 ~ 0.73	−14.6 ~ 12.2	7.1 ~ 32.6
HUC 09020109	SMFMX (7.0), TIMP (0.3), SMTMP (2.5), SURLAG (15.0), MSK_CO1 (1.2), MSK_CO2 (1.2), ESCO (0.95), GWQMN (0), CN2 (+8), ALPHA_BF (+0.3)	0.55 ~ 0.65	−3.6 ~ −2.1	7.1 ~ 27.8	−4.96 ~ 0.76	−18.0 ~ 270.6	4.7 ~ 60.6
HUC 09020202	SMFMX (10.0), TIMP (0.9), SMTMP (2.5), SURLAG (1.0), MSK_CO1 (0.6), MSK_CO2 (0.6), ESCO (0.95), GWQMN (0), CN2 (+10%)	0.18	5.1	12.9	–	–	–
HUC 09020203	SMFMX (10.0), TIMP (0.5), SMTMP (4.0), SURLAG (1.0), MSK_CO1 (1.8), MSK_CO2 (1.8), ESCO (0.95), GWQMN (0), CN2 (+10%)	−0.01 ~ 0.63	−88.5 ~ −44.2	33.8 ~ 97.5	–	–	–
HUC 09020204	SMFMX (8), TIMP (0.172), SMTMP (2.5), SURLAG (1), MSK_CO1 (1.8), MSK_CO2 (1.8), ESCO (0.95), GWQMN (0), CN2 (+3.0)	0.87 ~ 0.91	−9.2 ~ −5.6	7.4 ~ 21.2	–	–	–
HUC 09020205	SMFMX (8), TIMP (0.05), SMTMP (1.2), SURLAG (0.85), MSK_CO1 (0.65), MSK_CO2 (0.65), ESCO (0.95), GWQMN (0), CN2 (default)	0.65 ~ 0.74	−28.9 ~ −2.7	26.7 ~ 39.0	–	–	–
HUC 09020301	SMFMX (8), TIMP (0.2), SMTMP (3.5), SURLAG (4), MSK_CO1 (1), MSK_CO2 (3), ESCO (0.95), GWQMN (0), CN2 (default)	–	–	–	–	–	–
HUC 09020307	SMFMX (6.5), TIMP (0.25), SMTMP (1.5), SURLAG (1), MSK_CO1 (3.5), MSK_CO2 (3.5), ESCO (0.95), GWQMN (0), CN2 (+3.0)	0.90	-9.9	10.9	–	–	–
HUC 09020308	SMFMX (6.0), TIMP (0.9), SMTMP (2.8), SURLAG (1), MSK_CO1 (0.5), MSK_CO2 (3.5), ESCO (0.95), GWQMN (0), CN2 (default)	0.67 ~ 0.69	−7.6 ~ 15.2	14.6 ~ 18.3	–	–	–
HUC 09020310	SMFMX (8), TIMP (0.5), SMTMP (4), SURLAG (2), MSK_CO1 (3), MSK_CO2 (1.3), ESCO (0.95), GWQMN (0), CN2 (default)	0.77	−20.3	31.9	–	–	–
HUC 09020311	SMFMX (6.5), TIMP (0.15), SMTMP (1.5), SURLAG (1), MSK_CO1 (1.2), MSK_CO2 (1.2), ESCO (0.95), GWQMN (0), CN2 (default)	–	–	–	–	–	–
HUC 09020313	SMFMX (6.5), TIMP (0.15), SMTMP (1.5), SURLAG (1), MSK_CO1 (1.2), MSK_CO2 (1.2), ESCO (0.95), GWQMN (0), CN2 (default)	0.75 ~ 0.97	−12.9 ~ 16.4	5.2 ~ 14.7	–	–	–

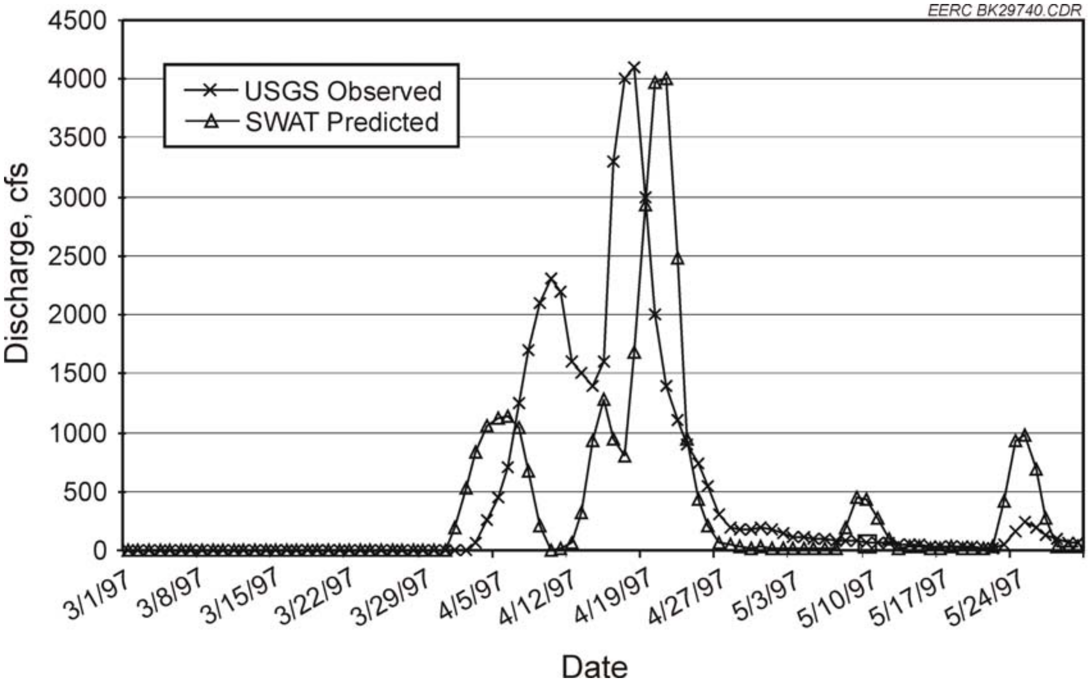


Figure C-9. The model-predicted vs. observed stream flow hydrographs at Shelly (USGS 05067500) in the Marsh River Watershed (HUC 09020107). The Nash–Sutcliffe coefficient $E_j^2 = 0.27$.

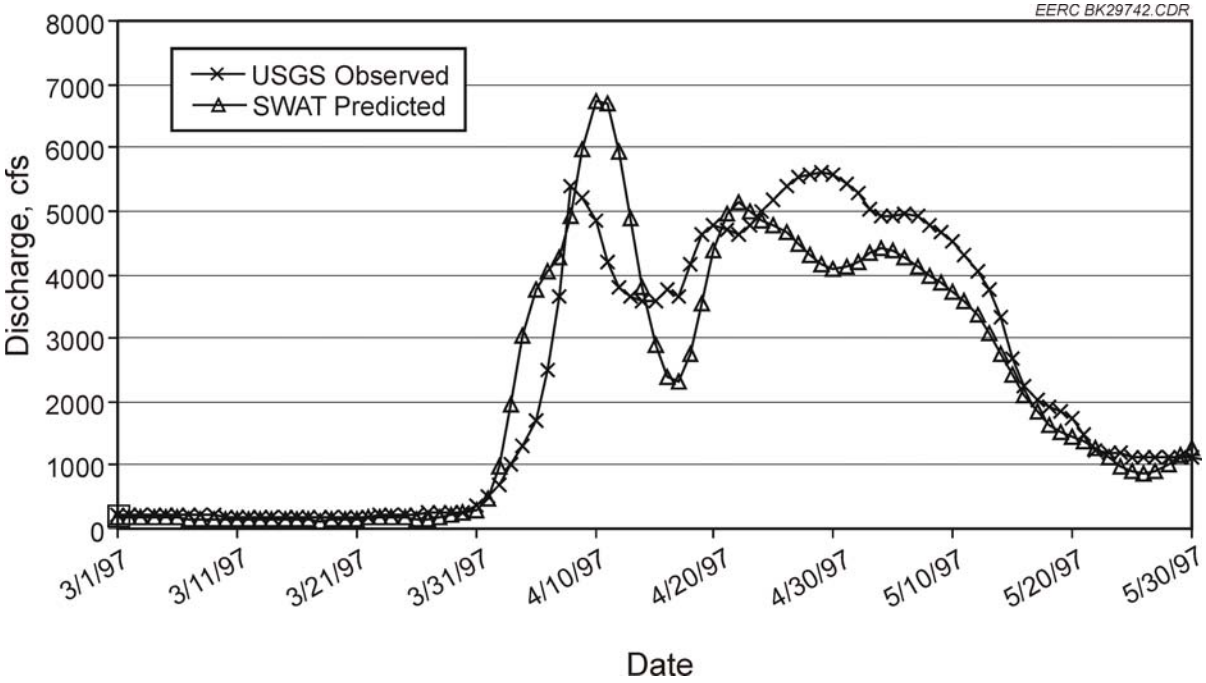


Figure C-10. The model-predicted vs. observed stream flow hydrographs at Kindred (USGS gauging station 05059000) in the Lower Sheyenne River Watershed (HUC 09020204). The Nash–Sutcliffe coefficient $E_j^2 = 0.91$.

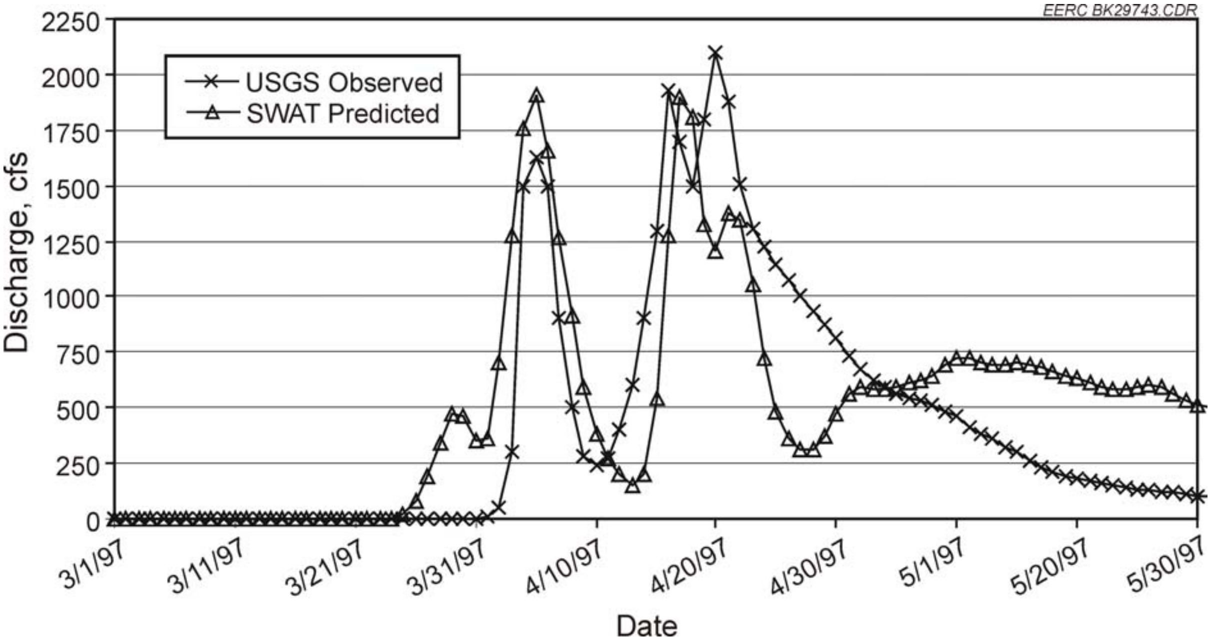


Figure C-11. The model-predicted vs. observed stream flow hydrographs at Minto (USGS gauging station 05085000) in the Forest River Watershed (HUC 09020308). The Nash–Sutcliffe coefficient $E_j^2 = 0.69$.

MODELED FLOW REDUCTIONS IN THE RED RIVER BASIN WATERSHEDS

Waffle Scenarios

For each modeling domain listed in Table C-4, three Waffle storage scenarios were generated and evaluated to determine peak flow reductions at the outlets of each tributary and, in some cases, in upstream reaches of the tributaries. Each of these storage scenarios was based on the EERC's most conservative storage estimate, corresponding to a volume of approximately 583,400 acre-ft. Scenario I (S-I) modeled 100% of the conservative Waffle storage volume, whereas Scenario II (S-II) and Scenario III (S-III) evaluated 75% and 50% of the conservative storage volume, respectively. This was done to estimate the flood reduction effects if only a certain percentage of Waffle storage was utilized during a flood event like 1997. To obtain the storage volumes that are 75% and 50% of the original estimates, Waffle storage areas in each watershed were randomly eliminated by 25% and 50%, respectively, and the total storage volume was recalculated.

Table C-7 lists the three Waffle storage volumes for each RRB watershed, except for HUC 09020202 (Upper Sheyenne), HUC 09020203 (Middle Sheyenne), HUC 09020302 (Red Lakes), and HUC 09020314 (Roseau). The runoff generated in HUC 09020202 (Upper Sheyenne) and HUC 09020203 (Middle Sheyenne) is regulated by the Baldhill Dam, which could offset the effects of Waffle storage on Red River flow and stage reductions. Similarly, the runoff generated in HUC 09020302 is regulated by the Red Lake Dam. The Roseau River (HUC 09020314) does not directly contribute runoff to the Red River in the United States. Thus Waffle storage areas for these four modeling domains were not modeled and are not shown in Table C-7. In addition, the

Waffle storage volume listed in Table C-7 for the Red Lake River Watershed (HUC 09020303) also includes the storage volumes from Thief and Clearwater River Watersheds (HUC 09020304 and 09020305). Details on the identification of potential Waffle storage areas across the RRB are documented in Section 2.3 of this report.

Readers should be aware that the volumes listed in Table C-7 for 100% of identified Waffle storage are somewhat different than the values presented in Section 2.3 of this report. This discrepancy is attributable to three main factors. First, in Section 2.3, storage is summarized in terms of the USGS 8-digit HUCs provided by the NHD, whereas the corresponding values in Table C-7 were reported in terms of the modeling domains delineated by SWAT using the 30-m NED data. Although efforts were made to make the delineated boundaries closely match the corresponding ones provided by the NHD, a close examination indicated that these boundaries could be offset by as much as 10%. This small offset is considered acceptable given the coarse resolution of, and inherent errors in, the NED data. Second, the USGS 8-digit HUCs that cover both Minnesota and North Dakota, including the Bois de Sioux (09020101), Upper Red (09020104), Elm–Marsh (09020107), Sandhill–Wilson (09020301), and Lower Red (092020311) Watersheds, were split into two modeling domains, which lost 5% to 10% of the drainage areas adjacent to the Red River because of the coarse NED resolution. Finally, the GIS procedure used to clip the RRB Waffle storage map (reported in Section 2.3) might inappropriately include and/or exclude storage sections that intersect the boundaries of the delineated modeling domains. As a result, the modeled Waffle storage areas and volumes are less than the values originally identified in Section 2.3, which would make the analyzed Waffle effects on flood reduction more conservative.

The Waffle effects were measured by comparison of peak flow reductions as a result of Waffle storage (post-Waffle conditions) to peak flows without Waffle storage (pre-Waffle conditions) at the outlet of, and at key points within, each modeled watershed. The percent reduction in peak flow was calculated by:

$$\text{Effect} = \frac{(\text{post-Waffle peak}) - (\text{pre-Waffle peak})}{(\text{pre-Waffle peak})} \times 100\% \qquad \text{[Eq. 48]}$$

The evaluation of three Waffle storage scenarios (100%, 75%, and 50%) for all six aforementioned flood events leads to a possible 24 model runs per modeling domain (Figure C-12). The Waffle storage evaluations in most North Dakota modeling domains were limited to the 1997 flood event, and flow reductions were only evaluated at the tributary outlets. However, the evaluations for the Minnesota modeling domains were conducted for the six aforementioned historical flood events, and flow reductions were examined at the tributary outlet, as well as at other points of interest within the domains.

Table C-7. Waffle Storage Volumes of the Three Analyzed Scenarios: Scenario I (S-I), Scenario II (S-II), and Scenario III (S-III) (S-I considers 100% of the identified storage, whereas S-II and S-III evaluate 75% and 50% of the identified storage, respectively)

State	Modeling Domain	Watershed	S-I, ac-ft	S-II, ac-ft	S-III, ac-ft
MN	HUC 09020101	Rabbit	22,800	17,200	13,300
	HUC 09020102	Mustinka	6500	5200	3200
	HUC 09020103	Otter Tail	2400	1700	900
	HUC 09020104	Upper Red	38,900	29,400	16,700
	HUC 09020106	Buffalo	21,500	16,300	10,300
	HUC 09020107	Marsh	35,000	27,300	16,100
	HUC 09020108	Wild Rice MN	20,300	15,100	10,300
	HUC 09020301	Sandhill	16,300	12,800	9500
	HUC 09020303	Red Lake	60,700	46,900	31,600
	HUC 09020306	Grand Marais	25,200	18,800	12,400
	HUC 09020309	Snake	12,500	9200	5700
	HUC 09020311	Lower Red	36,100	27,400	16,100
	HUC 09020312	Two Rivers	18,500	14,600	8800
ND	HUC 09020101	Bois de Sioux	3300	2800	1800
	HUC 09020105	Wild Rice	27,000	21,000	13,100
	HUC 09020107	Elm	32,700	24,700	16,600
	HUC 09020109	Goose	20,400	14,600	11,300
	HUC 09020204	Lower Sheyenne	27,200	19,300	12,900
	HUC 09020205	Maple	14,200	10,400	7000
	HUC 09020301	Wilson	19,700	14,700	9800
	HUC 09020307	Turtle	5300	4100	3100
	HUC 09020308	Forest	5600	4600	2800
	HUC 09020310	Park	26,100	20,400	12,400
	HUC 09020311	Lower Red	16,000	12,600	7800
	HUC 09020313	Pembina	9200	7400	5100
Total			523,400	398,500	258,600

Representation of Waffle Storage Areas in the SWAT Models

As previously mentioned, Waffle storage was modeled using the pond function in SWAT. To accomplish this, the identified Waffle storage areas within a modeling domain (watershed) were allocated to each of the subbasins, resulting from the subdivision of the modeling domain for modeling purposes. Subsequently, for each subbasin, the allocated storage areas were lumped into one "synthetic" pond. The allocation was implemented by overlaying the SWAT-delineated subbasin layer with the storage areas layer (Figure C-13), whereas the allocated storage areas were lumped based on an algorithm developed through the project. Assuming that for a 1-mi by 1-mi section, the total storage volume can be proportionally partitioned into the subbasins covering the section, that is, a subbasin covering a larger area of the section can be assigned a greater portion of the storage volume (Figure C-14), the algorithm can be expressed as:

$$\mathrm{SCV}_i^j = \frac{\mathrm{SCA}_i^j}{259} \times \mathrm{TWV}_j \qquad \text{[Eq. 49]}$$

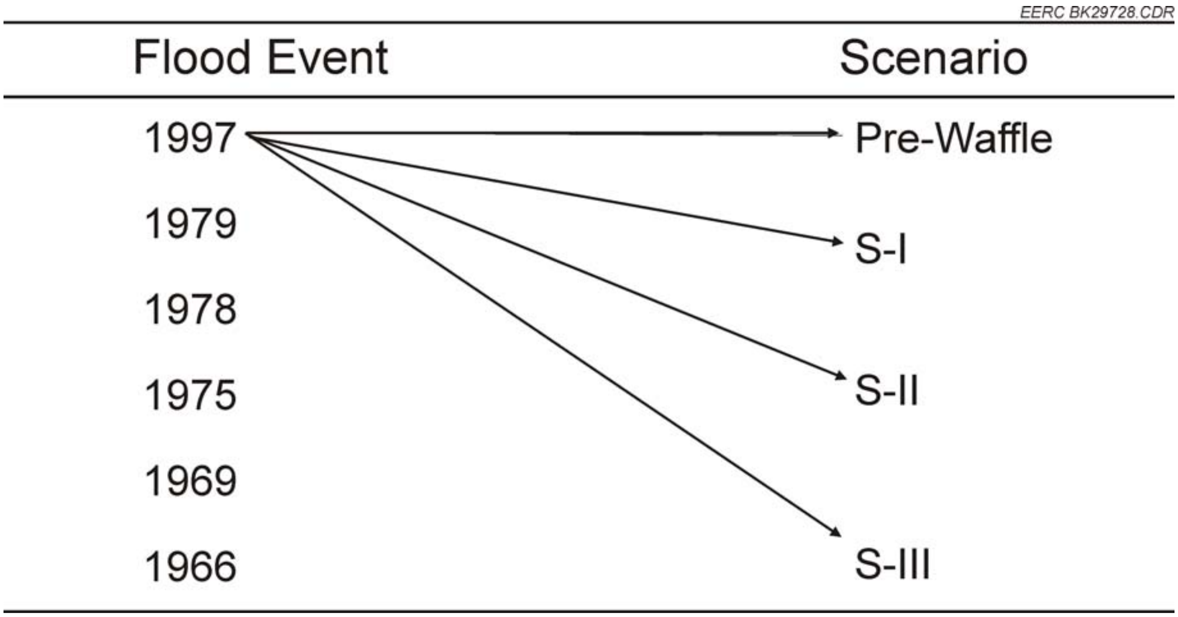


Figure C-12. For each modeling domain, there were 24 possible model runs. Scenario I (S-I) considered 100% of the identified storage, whereas Scenarios II and III (S-II and S-III) evaluated 75% and 50% of the identified storage, respectively.

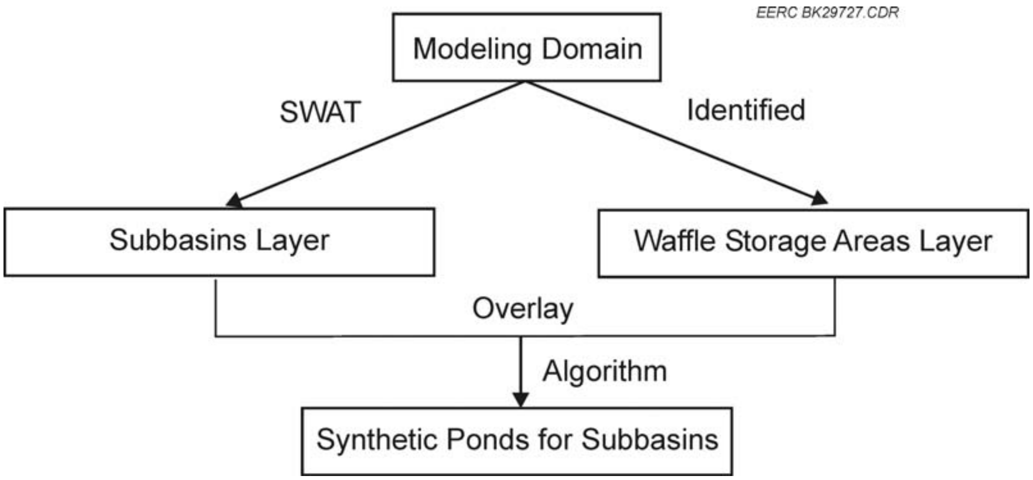


Figure C-13. Flowchart showing the approach for defining “synthetic” ponds.

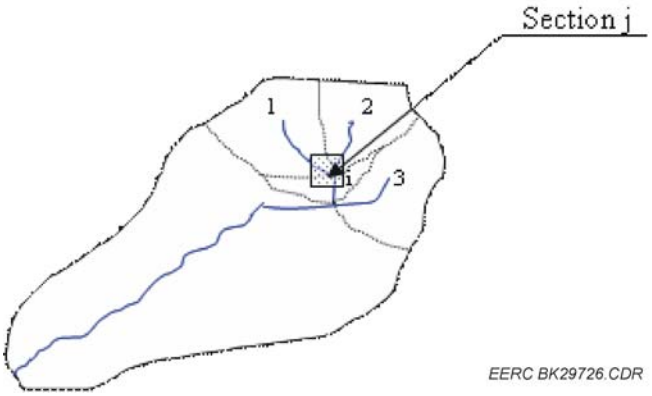


Figure C-14. Schematic showing Section j, which is covered by Subbasins 1, 2, …, i with areas of $SCA_1^j, SCA_2^j, \ldots, SCA_i^j$, respectively. $\sum_{m=1}^{i} SCA_m^j = 1\,mi^2$.

where SCA_i^j is the area of Section j covered by Subbasin i (ha); TWV_j is the identified total Waffle storage volume in Section j (ac-ft); and SCV_i^j is the storage volume in Section j that is allocated to Subbasin i (ac-ft).

The total storage volume in Subbasin i, $SynPV_i$, is defined as the summation of the storage sections that are both completely and partially included in the subbasin. Thus the synthetic pond for subbasin, i, is assumed to have a maximum storage equal to $SynPV_i$. Its corresponding maximum area, $SynPA_i$, is computed as:

$$SynPA_i = \frac{SynPV_i}{\bar{h}} \qquad \text{[Eq. 50]}$$

where $\bar{h}$ is the average depth of the Waffle storage areas in the watershed, within which the modeling domain is located. The values for $\bar{h}$ were determined based on the sample sections used to identify the Waffle storage areas across the RRB and are shown in Table C-8.

To define a synthetic pond, the seven parameters contained in Equations 7–14 need to be determined, including:

- The surface area of the pond when filled to the emergency spillway (SA_{em}).
- The surface area of the pond when filled to the principal spillway (SA_{pr}).
- The volume of water held in the pond when filled to the emergency spillway (V_{em}).
- The volume of water held in the pond when filled to the principal spillway (V_{pr}).
- The fraction of the subbasin area draining into the pond (fr_{imp}).
- The target pond volume for the day (V_{targ}).
- The number of days required for the pond to reach the target volume (ND_{targ}).

Table C-8. Average Depths of the Waffle Storage Areas in each of the RRB Watersheds (it should be noted that a watershed could include two modeling domains, as listed in Table C-4)

Name	USGS 8-Digit Hydrologic Unit Code	Average Depth	
		m	ft
Bois de Sioux	09020101	0.44	1.44
Buffalo	09020106	0.81	2.66
Clearwater	09020305	0.52	1.71
Eastern Wild Rice	09020108	0.69	2.26
Elm–Marsh	09020107	0.63	2.07
Forest	09020308	0.43	1.41
Goose	09020109	0.62	2.03
Grand Marais–Red	09020306	0.36	1.18
Lower Red	09020311	0.42	1.38
Lower Sheyenne	09020204	0.95	3.12
Maple	09020205	0.63	2.07
Middle Sheyenne	09020203	0.60	1.97
Mustinka	09020102	0.35	1.15
Otter Tail	09020103	0.57	1.87
Park	09020310	0.52	1.71
Pembina	09020313	0.59	1.94
Red Lake	09020303	0.37	1.21
Roseau	09020314	0.35	1.15
Sandhill–Wilson	09020301	0.36	1.18
Snake	09020309	0.34	1.12
Tamarac [1]	09020311	0.37	1.21
Thief	09020304	0.48	1.57
Turtle	09020307	0.64	2.10
Two Rivers	09020312	0.34	1.12
Upper Red	09020104	0.45	1.48
Upper Sheyenne	09020202	0.73	2.40
Western Wild Rice	09020105	0.71	2.33
Average Across RRB	–	0.53	1.73

[1] This river drains a partial area of the Lower Red Watershed. The depth should be used for the Waffle storage areas located in the area drained by the Tamarac River.

The standpipe proposed for the Waffle concept was modeled as an emergency spillway, and it was assumed that a 1-ft (0.31-m) freeboard existed between the standpipe opening and the lowest point along the synthetic pond banks (representative of the roads surrounding a section). To avoid overtopping the pond bank, the initiation of storage (ND_{targ}; Equation 14) was adjusted to prevent the pond from being overfilled from upstream runoff. In practice, the potential volume of runoff upstream of individual storage areas (as a function of precipitation) will need to be estimated for comparison with the capacity and outflow rate of the respective storage area. This information, used in conjunction with flood forecast models, can be used to develop operational plans for storage areas to help ensure that roads are not overtopped.

Given that the standpipe functions as an emergency spillway and the storage volumes identified through this study were equivalent to the volume of water when it reaches the top of the standpipe (i.e., the water volume assuming a 1-ft freeboard), then, for Subbasin I, SA_{em} and V_{em} can be determined by:

$$SA_{em} = SynPA_i \qquad \text{[Eq. 51]}$$

$$V_{em} = SynPV_i \qquad \text{[Eq. 52]}$$

Further, the lowest inlet elevation of the culvert(s) that would be modified to control water in the section would function as a principal spillway (if the canal gate were opened). The principal spillway was used to control when the water would be stored or released. Because at this inlet elevation the surface area and volume of water held in the pond would be negligible, in this study, SA_{pr} and V_{pr} were assumed to have small constant values as:

$$SA_{pr} = 0.1 \text{ ha} \qquad \text{[Eq. 53]}$$

$$V_{pr} = 0.81 \text{ ac-ft} = 0.1\times10^4 \text{ m}^3 \qquad \text{[Eq. 54]}$$

fr_{imp} was computed as:

$$fr_{imp} = \frac{5 \times SynPA_i}{DA_i} \qquad \text{[Eq. 55]}$$

where DA_i is the drainage area of Subbasin i (ha).

An examination of historical flow hydrographs indicated that the ideal storage period using the Waffle approach is 2 to 3 weeks. The storage period used by the Waffle field trials was 2 weeks, since it was assumed that 2 weeks was a fair balance between achieving downstream flow reductions and minimizing potential delays in planting on agricultural land. The evaluation of Waffle storage using the SWAT models assumed a storage period (ND_{targ}) of a maximum of 20 days to try to encompass the variation in flood crest dates between different flood events. In the event of Waffle implementation, the actual storage period may be much less than 20 days, depending on the date of the flood crest. ND_{targ} was equally allocated around the peak flow date, as measured by the nearest gauging station. In other words, if ND_{targ} was 20 days, the gate was assumed to be closed: 10 days ($ND_{targ}/2$) before the peak date and to be opened 10 days ($ND_{targ}/2$) after the peak. While there are numerous methods to model operation of storage areas, the approach used in this study is commonly utilized in feasibility and planning studies and, therefore, was appropriate for the Waffle study. Therefore, within the SWAT models, V_{targ} was set as:

$$V_{t\arg} = \begin{cases} SynPV_i & \rightarrow \\ 0.0 & \rightarrow \end{cases} \quad \frac{\text{During the storage period of } ND_{targ} \text{ days}}{\text{Outside of the storage period}} \qquad \text{[Eq. 56]}$$

RESULTS AND DISCUSSION

For a 1997-type flood, S-I was predicted to result in a reduction of peak flows at outlets of the modeling domains by 0.3% to 59.2%, whereas S-II and S-III would reduce the peaks by 0.3% to 45.2% and 0.0% to 27.2%, respectively (Table C-9 and Figures C-15 and C-16). The percent reduction is larger overall for watersheds with a greater south–north width than for those with a greater east–west length. For example, the Upper Red River Watershed (modeling domain HUC

Table C-9. Effects on Reducing 1997-Type Peaks as Measured at the Outlets of the Modeling Domains for the Three Waffle Scenarios

State	Modeling Domain	Watershed	Pre-Waffle	Scenario I (S-I)		Scenario II (S-II)		Scenario III (S-III)	
			Peak, cfs	Peak, cfs	Effect, %	Peak, cfs	Effect, %	Peak, cfs	Effect, %
MN	HUC 09020101	Rabbit	6185	5000	19.2	5320	14.0	5458	11.8
	HUC 09020102	Mustinka	9915	9735	1.8	9780	1.4	9830	0.9
	HUC 09020103	Otter Tail	1615	1610	0.3	1610	0.3	1615	0.0
	HUC 09020104	Upper Red	1250	510	59.2	685	45.2	910	27.2
	HUC 09020106	Buffalo	8700	8575	1.4	8610	1.0	8640	0.7
	HUC 09020107	Marsh	7910	5540	30.0	6385	19.3	7215	8.8
	HUC 09020108	Wild Rice MN	10,735	10,095	6.0	10,255	4.5	10,405	3.1
	HUC 09020301	Sandhill	4515	4015	11.1	4100	9.2	4250	5.9
	HUC 09020303	Red Lake	20,070	19,090	4.9	19,270	4.0	19,540	2.6
	HUC 09020306	Grand Marais	680	385	43.4	450	33.8	500	26.5
	HUC 09020309	Snake	14,480	13,835	4.5	13,995	3.3	14,175	2.1
	HUC 09020311	Lower Red	3890	3190	18.0	3360	13.6	3480	10.5
	HUC 09020312	Two Rivers	4775	4100	14.1	4230	11.4	4445	6.9
ND	HUC 09020101	Bois de Sioux	2428	2080	14.3	2084	14.2	2090	13.9
	HUC 09020105	Wild Rice	8529	8084	5.2	8264	3.1	8296	2.7
	HUC 09020107	Elm	4885	3460	29.2	3760	23.0	4120	15.7
	HUC 09020109	Goose	7695	7430	3.4	7508	2.4	7554	1.8
	HUC 09020204	Lower Sheyenne	4775	4708	1.4	4729	1.0	4747	0.6
	HUC 09020205	Maple	6586	6488	1.5	6516	1.1	6537	0.7
	HUC 09020301	Wilson	5745	4780	16.8	5135	10.6	5477	4.7
	HUC 09020307	Turtle	2265	2168	4.3	2188	3.4	2207	2.6
	HUC 09020308	Forest	2956	2768	6.4	2826	4.4	2906	1.7
	HUC 09020310	Park	7374	6286	14.7	6724	8.8	7335	0.5
	HUC 09020311	Lower Red	3456	2770	19.8	2878	16.7	2999	13.2
	HUC 09020313	Pembina	19,205	18,680	2.7	18,774	2.2	18,929	1.4
Average			6825	6215	13.3	6377	10.1	6546	6.7

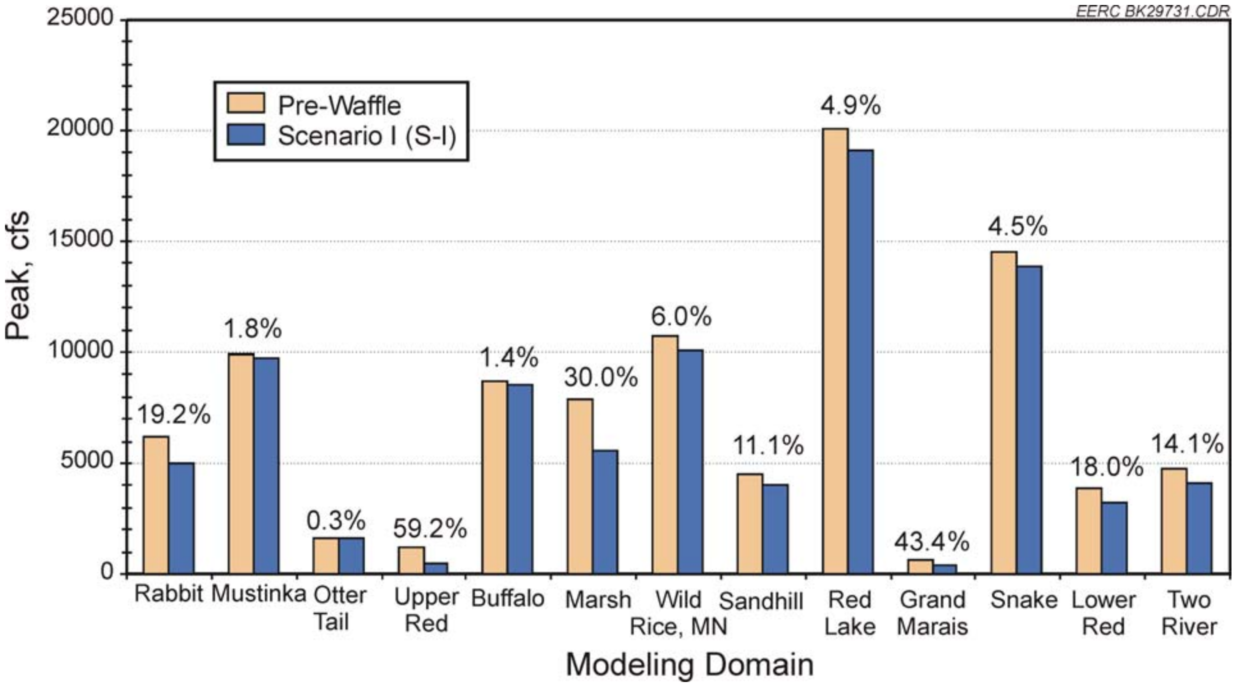


Figure C-15. Plot showing the predicted reductions in 1997-type flood peaks at the outlets of Minnesota modeling domains as a result of implementing Waffle Scenario I.

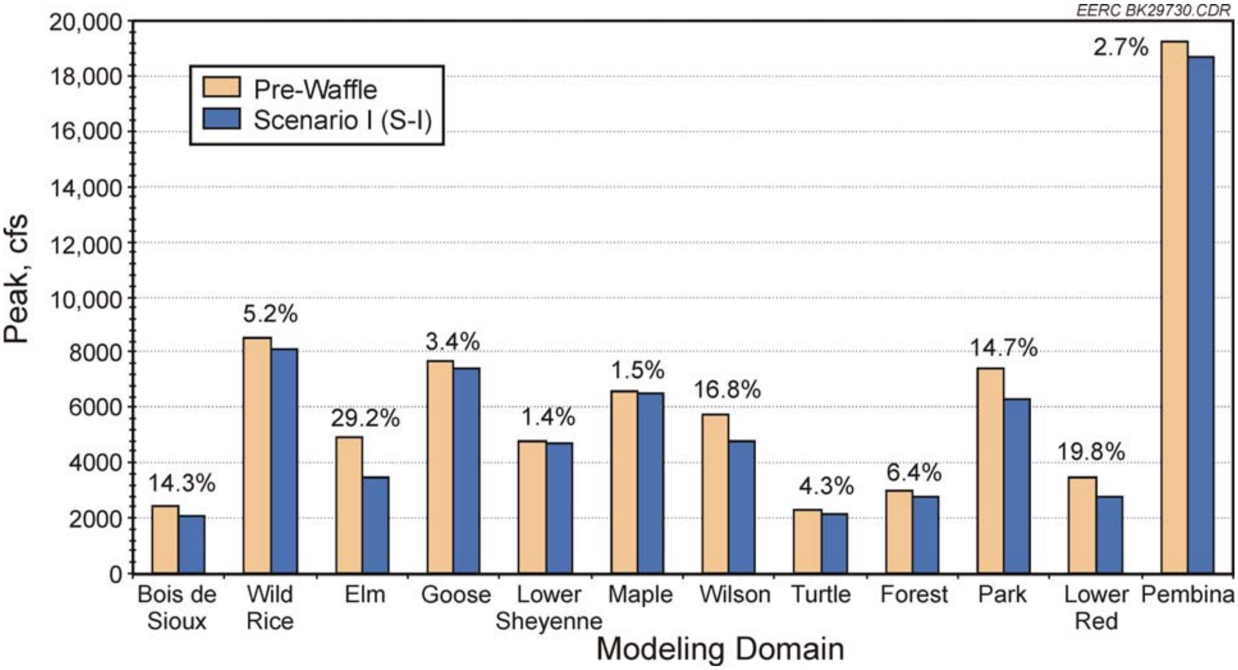


Figure C-16. Plot showing the predicted reductions in 1997-type flood peaks at the outlets of North Dakota modeling domains as a result of implementing Waffle Scenario I.

09020104) has a south–north width much greater than its east–west length and was predicted to have a reduction of 59.2%. The Lower Sheyenne River watershed (modeling domain HUC 09020204), on the other hand, has a south–north width much smaller than its east–west length and was predicted to have a reduction of only 1.4%. One explanation for this may be that the dominant drainage area of a watershed with a larger width-to-length ratio is adjacent to the watershed outlet. As a result, the effect of the Waffle storage areas can be achieved without much dissipation. In contrast, the Waffle effect for a watershed with a smaller width-to-length ratio tends to greatly dissipate before the effect can be noticed at the watershed outlet. Another explanation is that a watershed with a greater width-to-length ratio tends to be dominated by overland processes rather than channel processes; that is, in general, precipitation has a longer travel time on the land than along the associated streams. Thus overland runoff has a higher chance to be intercepted and regulated by the Waffle storage areas before it becomes concentrated stream flows. Because the Waffle storage areas are scattered across the watershed and an individual Waffle storage area (i.e., a section) usually has limited storage capacity, the effect of the storage areas on handling the concentrated stream flows is much lower than that on regulating the corresponding overland runoff. This indicates that cumulative effects of Waffle storage areas offer more overall benefit than any one individual storage area.

As expected, watersheds with more Waffle storage areas experienced greater flow reductions. For all watersheds, S-I was predicted to have a greater effect than S-II which, in turn, was predicted to have larger effects than S-III (Table C-9). The average difference in effect between two consecutive scenarios (i.e., S-I versus S-II and S-II versus S-III) was determined to be approximately 3.2%. The watersheds with smaller drainage areas and/or greater width-to-length ratios are more sensitive to changes in Waffle storage areas. For example, in the Marsh River Watershed, the reduction difference between consecutive storage scenarios was about 10.5%, whereas in modeling domain 09020303 (includes the Red Lake, Clearwater, and Thief River Watersheds), which has a much larger drainage area of 3533 mi^2, the reduction difference was only 1%. This is an indication that the Waffle may be more effective in controlling overland runoff than concentrated stream flows. Compared with conventional reservoirs, which are usually situated on drainage channels and intercept all upstream stream flows, the Waffle reduces flood peaks as a result of the cumulative effects of individual, small storage areas.

In addition, the spatial distribution of the Waffle storage areas within a watershed (modeling domain) is also important for flood reduction. For S-I, the Rabbit and Buffalo River Watersheds were identified to have near-equivalent Waffle storage volumes (22,783.87 acre-ft versus 21,495.07 acre-ft; Table C-7). However, the spatial locations of the storage areas within the inclusive watersheds are distinctly different (Figure C-17). In the Buffalo River Watershed, the Waffle storage areas are primarily located in the lower portion, where the hydrologic processes were dominated by concentrated stream flows. As a result, Waffle storage would have a very limited effect, as indicated by the small percentage reduction of 1.4% for the peak at the watershed outlet. In contrast, the Waffle storage areas in the Rabbit River Watershed cover most of the upland areas that have hydrologic processes primarily dominated by overland runoff. This spatial distribution is ideal for achieving flood reduction using the Waffle concept, as indicated by the large percentage reduction of 19.2% for the peak at the watershed outlet.

The importance of the spatial distribution of the Waffle storage areas on flood reduction for a watershed can be further verified by examining the percentage reductions at points of interest within the watershed. Tables C-10 to C-24 present the predicted percentage reductions of the peaks as a result of S-I at the selected evaluation points within the Minnesota modeling domains and the Elm River Watershed (modeling domain HUC 09020107) in North Dakota. The locations of these evaluation points are depicted in Figures C-18 to C-32. For the 1997-type flood, the predicted flood reductions within the Rabbit River Watershed vary from 4.1% at one location (Loc4) to 19.2% at another (Loc2; Figure C-20 and Table C-10). For the Red Lake River Watershed (modeling domain HUC 09020303), while the S-I was predicted to reduce the peak at the watershed outlet by only 4.9%, the percentage reduction at Loc3 (Figure C-27) could be as much as 9.7% (Table C-18). The similar spatial variations can be observed by examining the results for the other watersheds or modeling domains. Different from the percentage reduction of the peak at the outlet of a watershed, the spatial variation of the flood reductions seems to be irrelevant to the watershed shape as measured by the width-to-length ratio. Instead, the spatial variation is closely related to the spatial distribution of the Waffle storage areas within the watershed. For a watershed with the storage areas scattered across the drainage area, the corresponding flood reductions tend to exhibit a larger spatial variation. For example, compared with that within the Rabbit River Watershed, the predicted flood reductions within the Buffalo River Watershed have a spatial variation of less than 0.7% (Figure C-22 and Table C-14).

The flood reductions would also vary from one flood event to another (Tables C-10 to C-24). For a watershed, the flood reductions tend to be larger for a flood event with a smaller magnitude of peak. For example, at the outlet of the Rabbit River Watershed, the 1969 flood peak (1590 cfs) was much higher than the peaks that occurred in 1979 (690 cfs), 1978 (445 cfs), 1975 (575 cfs), and 1966 (520 cfs; Figure C-18 and Table C-10). The predicted reduction as a result of the S-I for the 1969-type flood is about 57% of that for the other three historical flood events. In addition, the shape of the flow hydrographs is also a determinative factor for the flood reductions, particularly at evaluation points where the channel process is dominant. For the Rabbit River Watershed, although the flood peak in 1969 was larger than that in 1997, the predicted reductions for the 1969-type flood are higher than the corresponding values for 1997

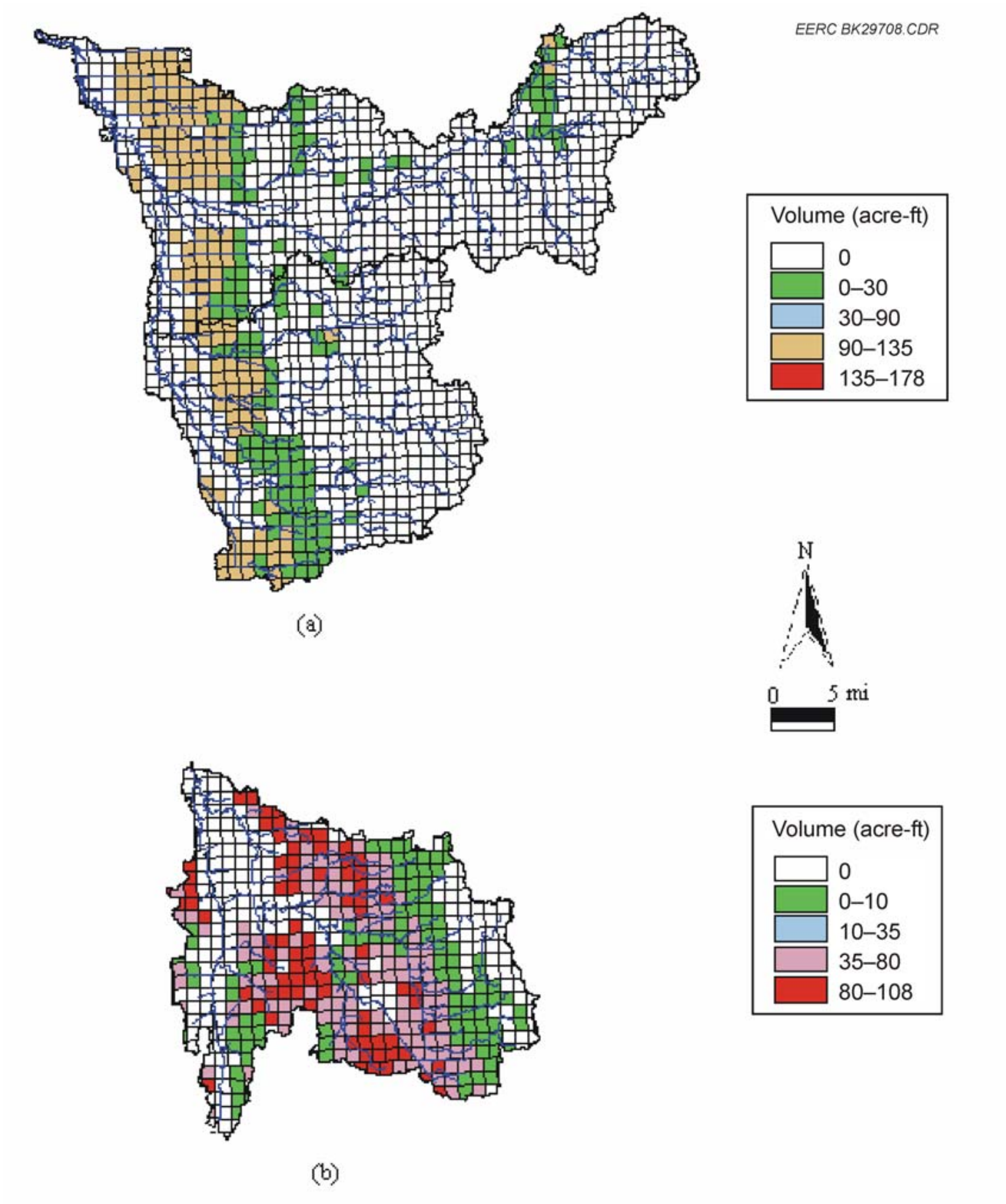


Figure C-17. Map showing the spatial distribution of the Waffle Scenario I storage areas within the (a) Buffalo River Watershed (modeling domain HUC 09020106) and (b) Rabbit River Watershed (modeling domain HUC 09020101).

Table C-10. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Rabbit River Watershed (HUC 09020101), Shown in Figure C-19, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2			Loc3			Loc4		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	6125	5000	−18.4	6185	5000	−19.2	325	295	−9.2	740	710	−4.1
1979	4410	3180	−27.9	4535	3270	−27.9	285	215	−24.6	690	490	−29.0
1978	3235	2480	−23.3	3215	2460	−23.5	175	130	−25.7	445	340	−23.6
1975	3725	2745	−26.3	3635	2675	−26.4	250	180	−28.0	575	425	−26.1
1969	11,320	9510	−16.0	11,435	9515	−16.8	635	510	−19.7	1590	1360	−14.5
1966	3830	2870	−25.1	3875	2900	−25.2	215	160	−25.6	520	400	−23.1

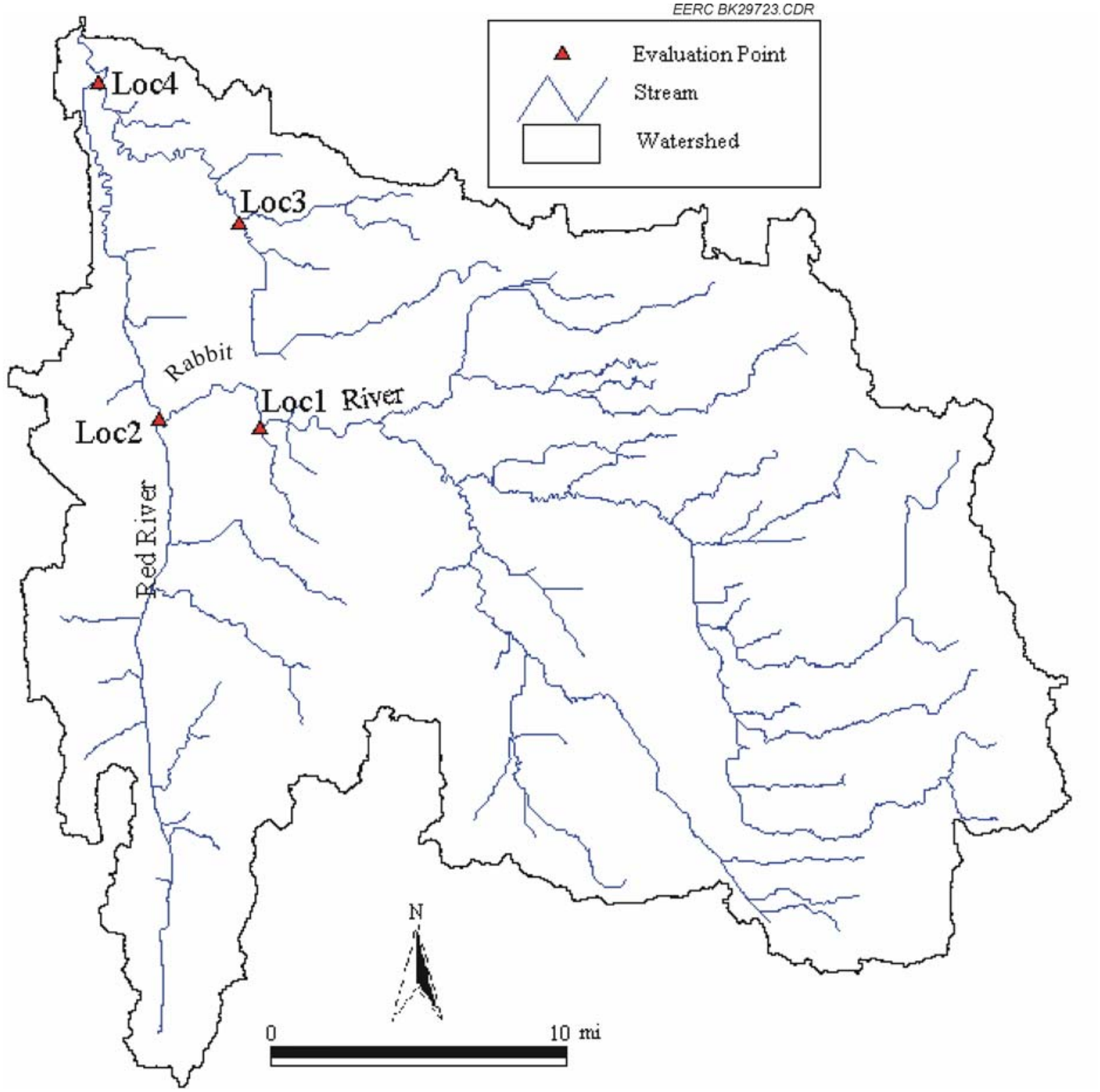


Figure C-18. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020101 (the Rabbit/Bois de Sioux Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-10.

Table C-11. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Mustinka River Watershed (HUC 09020102), Shown in Figure C-20, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	8830	8685	−1.6	9915	9735	−1.8
1979	9350	9240	−1.2	9585	9450	−1.4
1978	4490	4390	−2.2	4590	4470	−2.6
1975	7830	7565	−3.4	8115	7870	−3.0
1969	15,170	14,835	−2.2	15,735	15,330	−2.6
1966	5635	5415	−3.9	5830	5620	−3.6

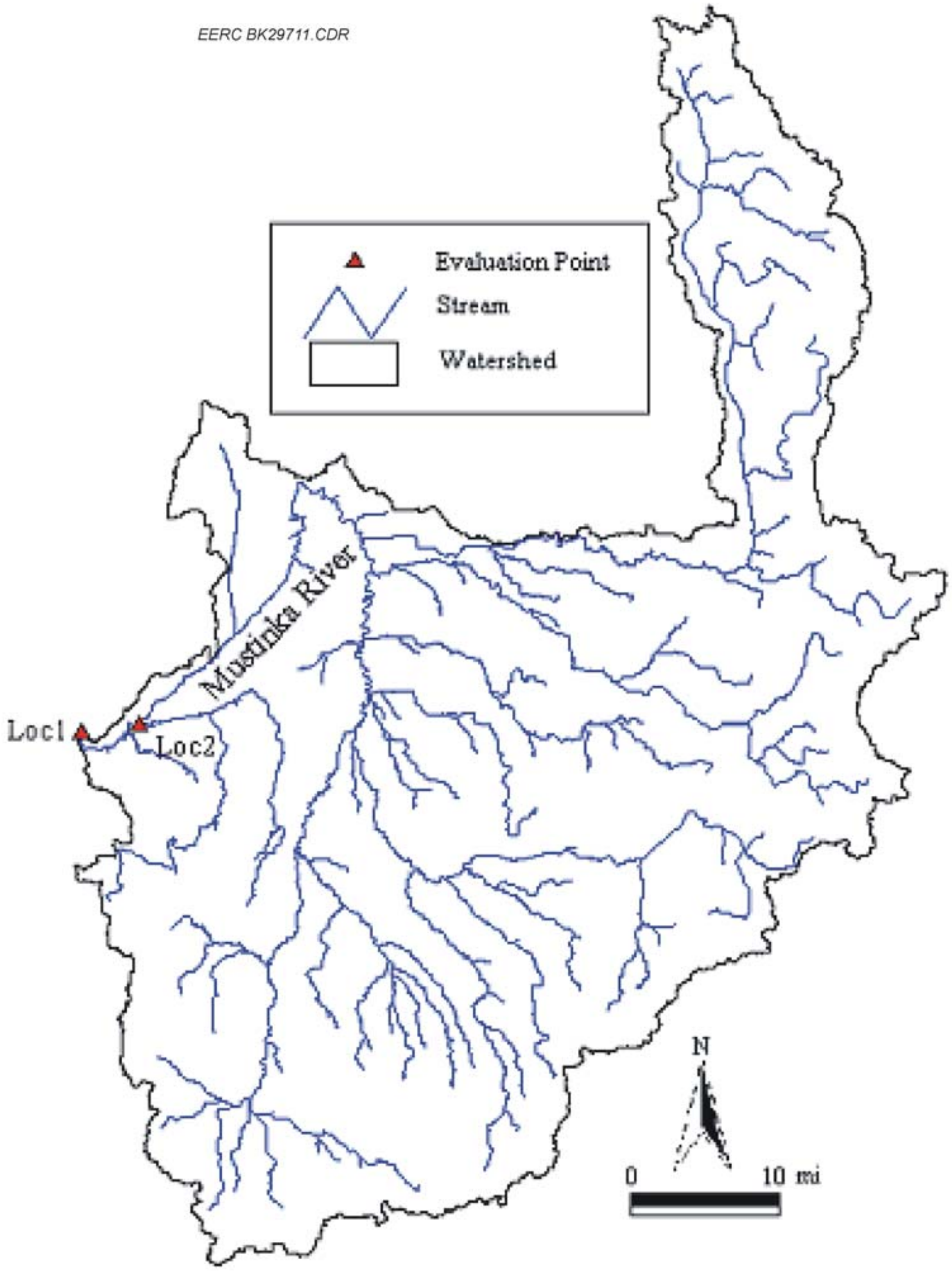


Figure C-19. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020102 (the Mustinka River Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-11.

Table C-12. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Otter Tail River Watershed (HUC 09020103), Shown in Figure C-21, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2			Loc3		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	790	790	0.0	940	940	0.0	1500	1500	0.0
1979	450	450	0.0	770	770	0.0	1130	1130	0.0
1978	405	405	0.0	755	755	0.0	1110	1110	0.0
1975	550	550	0.0	895	895	0.0	1390	1390	0.0
1969	635	635	0.0	785	785	0.0	1115	1115	0.0
1966	295	295	0.0	540	540	0.0	815	815	0.0

	Loc4			Loc5			Loc6		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	1465	1465	0.0	215	210	−2.3	1615	1610	−0.3
1979	1000	1000	0.0	120	120	0.0	1035	1035	0.0
1978	1000	1000	0.0	75	75	0.0	920	920	0.0
1975	1285	1285	0.0	100	100	0.0	1330	1330	0.0
1969	1070	1070	0.0	160	155	−3.1	1165	1165	0.0
1966	735	735	0.0	70	70	0.0	775	770	−0.6

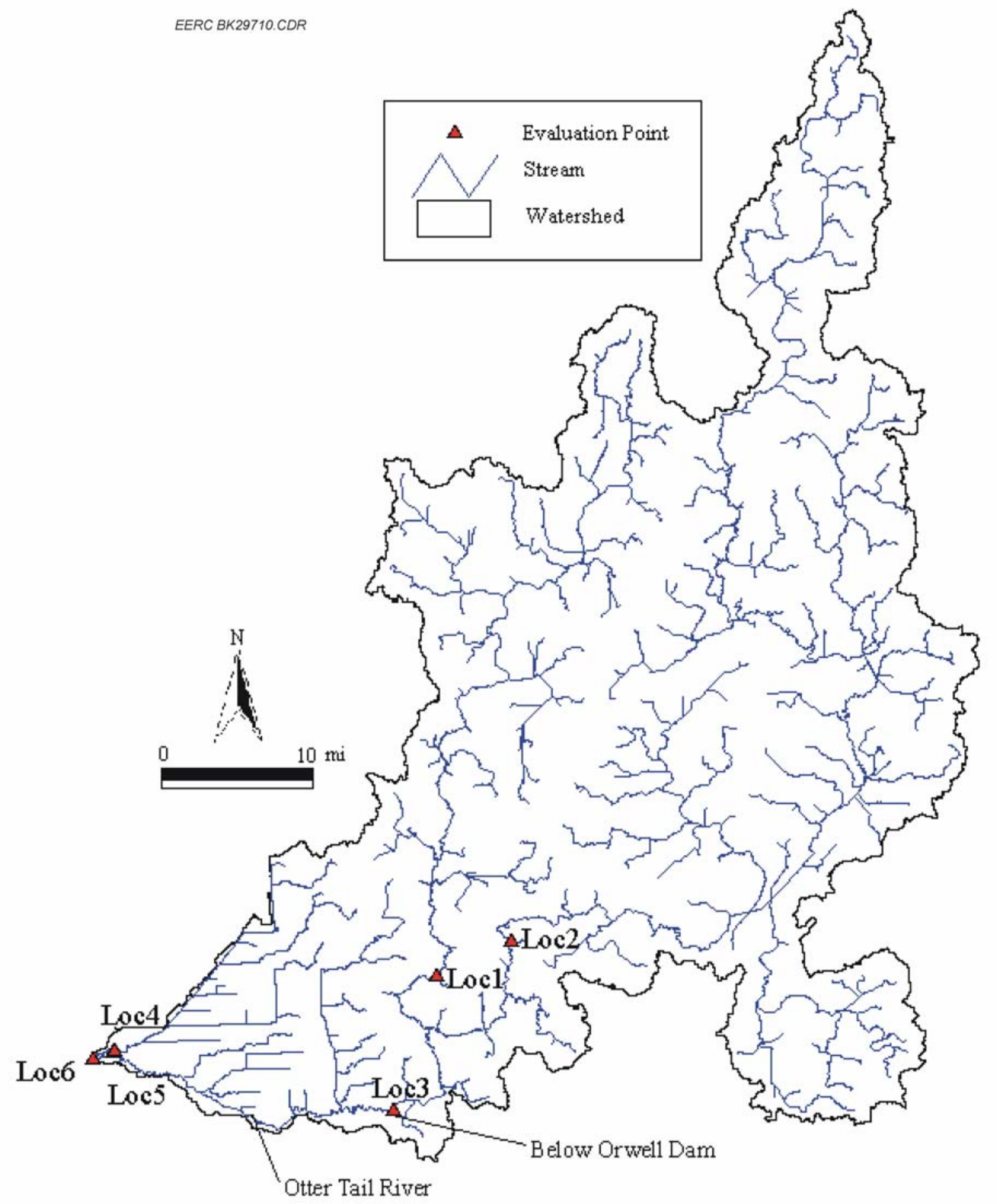


Figure C-20. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020103 (the Otter Tail River Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-12.

Table C-13. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Upper Red River Watershed (HUC 09020104), Shown in Figure C-22, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2			Loc4			Loc5		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I (cfs)	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	995	550	−44.7	990	545	−44.9	650	310	−52.3	1250	510	−59.2
1979	815	370	−54.6	800	360	−55.0	430	235	−45.3	995	675	−32.2
1978	675	335	−50.4	675	335	−50.4	385	230	−40.3	820	445	−45.7
1975	1035	510	−50.7	1025	510	−50.2	500	210	−58.0	810	335	−58.6
1969	2025	1200	−40.7	2000	1185	−40.8	985	590	−40.1	1855	925	−50.1
1966	560	400	−28.6	555	390	−29.7	500	235	−53.0	980	450	−54.1

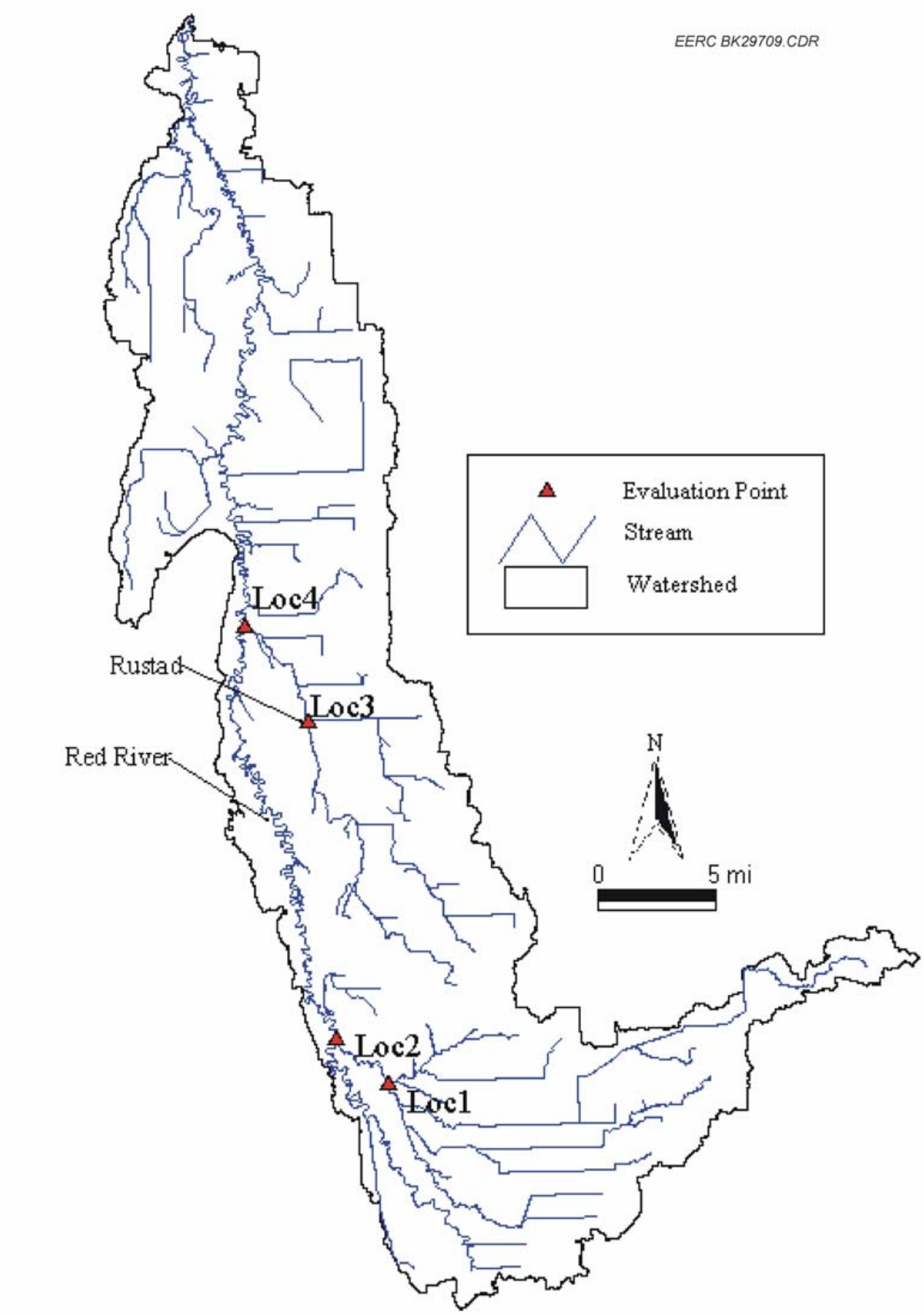


Figure C-21. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020104 (the Upper Red River Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-13.

Table C-14. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Buffalo River Watershed (HUC 09020106), Shown in Figure C-23, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2			Loc3		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	355	355	0.0	5840	5750	−1.5	2310	2300	−0.4
1979	180	180	0.0	2790	2740	−1.8	930	925	−0.5
1978	390	390	0.0	3395	3345	−1.5	1950	1940	−0.5
1975	260	260	0.0	3025	2975	−1.7	1075	1070	−0.5
1969	545	545	0.0	6295	6200	−1.5	1655	1640	−0.9
1966	215	215	0.0	3055	3015	−1.3	1535	1530	−0.3

	Loc4			Loc5		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	8290	8220	−0.8	8700	8575	−1.4
1979	4375	4155	−5.0	5740	5335	−7.1
1978	5190	5135	−1.1	5525	5425	−1.8
1975	2855	2820	−1.2	3120	3055	−2.1
1969	9880	9780	−1.0	10,550	10,350	−1.9
1966	4940	4830	−2.2	5660	5455	−3.6

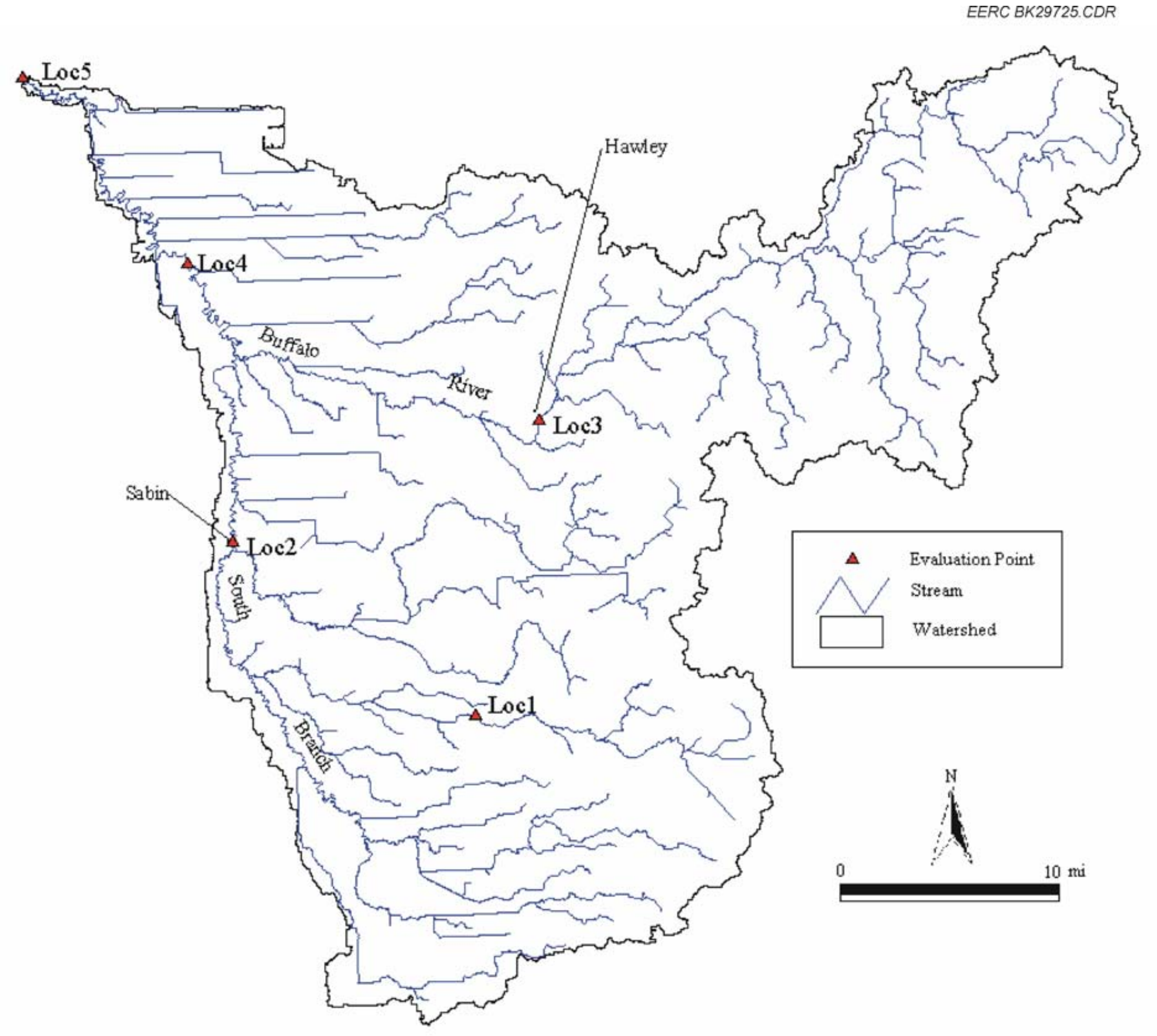


Figure C-22. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020106 (the Buffalo River Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-14.

Table C-15. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Marsh River Watershed (HUC 09020107), Shown in Figure C-24, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2			Loc3		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	815	680	−16.6	1405	1240	−11.7	3255	2610	−19.8
1979	975	880	−9.7	2110	1755	−16.8	3925	3085	−21.4
1978	465	295	−36.6	950	635	−33.2	1915	1155	−39.7
1975	535	380	−29.0	1290	900	−30.2	2145	1345	−37.3
1969	700	550	−21.4	1555	1195	−23.2	3230	2320	−28.2
1966	285	210	−26.3	765	540	−29.4	1130	830	−26.5

	Loc4			Loc5		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	4010	3240	−19.2	7910	5540	−30.0
1979	4700	3520	−25.1	9065	6640	−26.8
1978	2285	1280	−44.0	4395	2120	−51.8
1975	2330	1430	−38.6	4625	2540	−45.1
1969	3810	2540	−33.3	7470	4455	−40.4
1966	1370	910	−33.6	2655	1670	−37.1

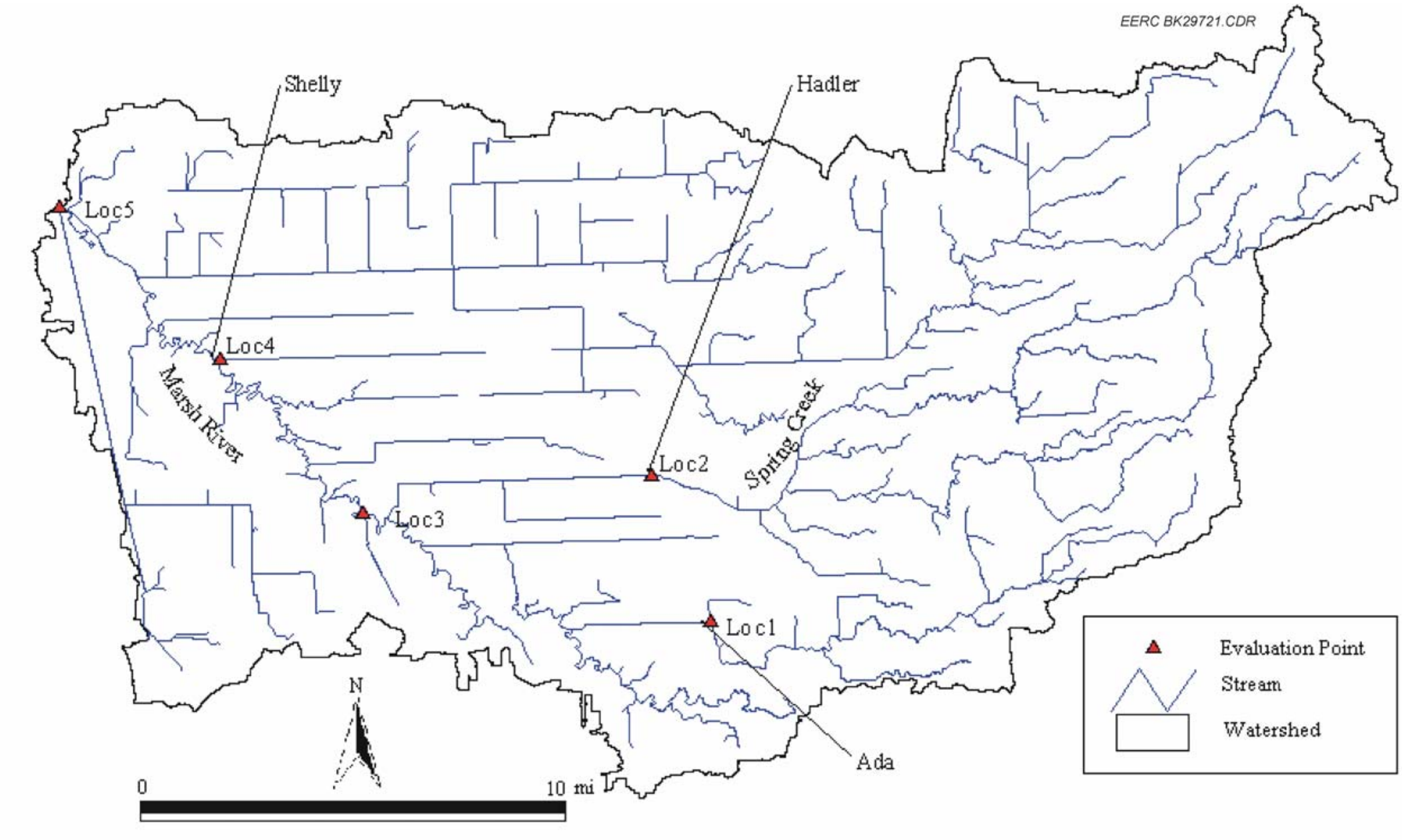


Figure C-23. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020107 (the Marsh River Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-15.

Table C-16. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Minnesota Wild Rice River Watershed (HUC 09020108), Shown in Figure C-25, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2			Loc3			Loc4		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	1460	1430	−2.1	845	835	−1.2	6135	5920	−3.5	8160	7875	−3.5
1979	1020	1010	−1.0	1070	1045	−2.3	4920	4730	−3.9	6055	5825	−3.8
1978	1185	1175	−0.8	830	810	−2.4	5040	4875	−3.3	5785	5600	−3.2
1975	850	845	−0.6	550	545	−0.9	2970	2880	−3.0	3705	3580	−3.4
1969	710	705	−0.7	645	645	0.0	4235	4090	−3.4	5680	5440	−4.2
1966	395	390	−1.3	325	325	0.0	2730	2625	−3.8	3400	3240	−4.7

	Loc5			Loc6			Loc7		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	945	875	−7.4	10,470	9830	−6.1	10,735	10,095	−6.0
1979	720	670	−6.9	7365	6950	−5.6	7560	7130	−5.7
1978	750	700	−6.7	7055	6690	−5.2	7145	6785	−5.0
1975	565	525	−7.1	4790	4465	−6.8	4950	4635	−6.4
1969	765	705	−7.8	7355	6810	−7.4	7615	7085	−7.0
1966	370	340	−8.1	4000	3770	−5.8	4140	3920	−5.3

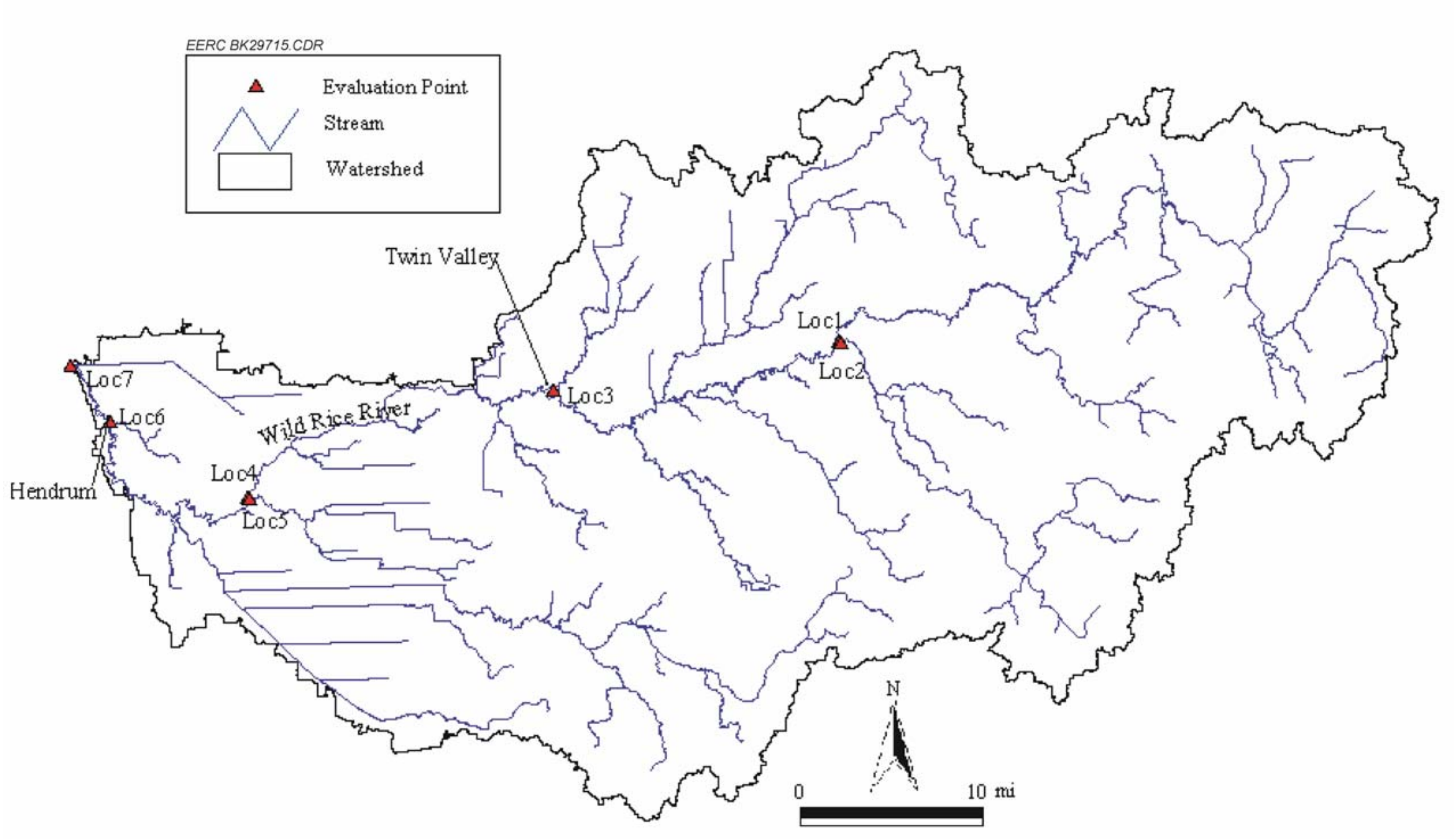


Figure C-24. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020108 (the MN Wild Rice River Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-16.

Table C-17. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Sandhill River Watershed (HUC 09020301), Shown in Figure C-26, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2			Loc3			Loc4		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	1480	1445	−2.4	285	280	−1.8	4215	3645	−13.5	4515	4015	−11.1
1979	1010	980	−3.0	270	255	−5.6	3395	2660	−21.6	3730	2940	−21.2
1978	1670	1645	−1.5	130	120	−7.7	2995	2430	−18.9	3060	2490	−18.6
1975	1070	1055	−1.4	100	95	−5.0	2285	1820	−20.4	2450	2020	−17.6
1969	1745	1690	−3.2	220	200	−9.1	3645	2780	−23.7	3725	2935	−21.2
1966	2630	2575	−2.1	180	165	−8.3	4095	3640	−11.1	4405	3905	−11.4

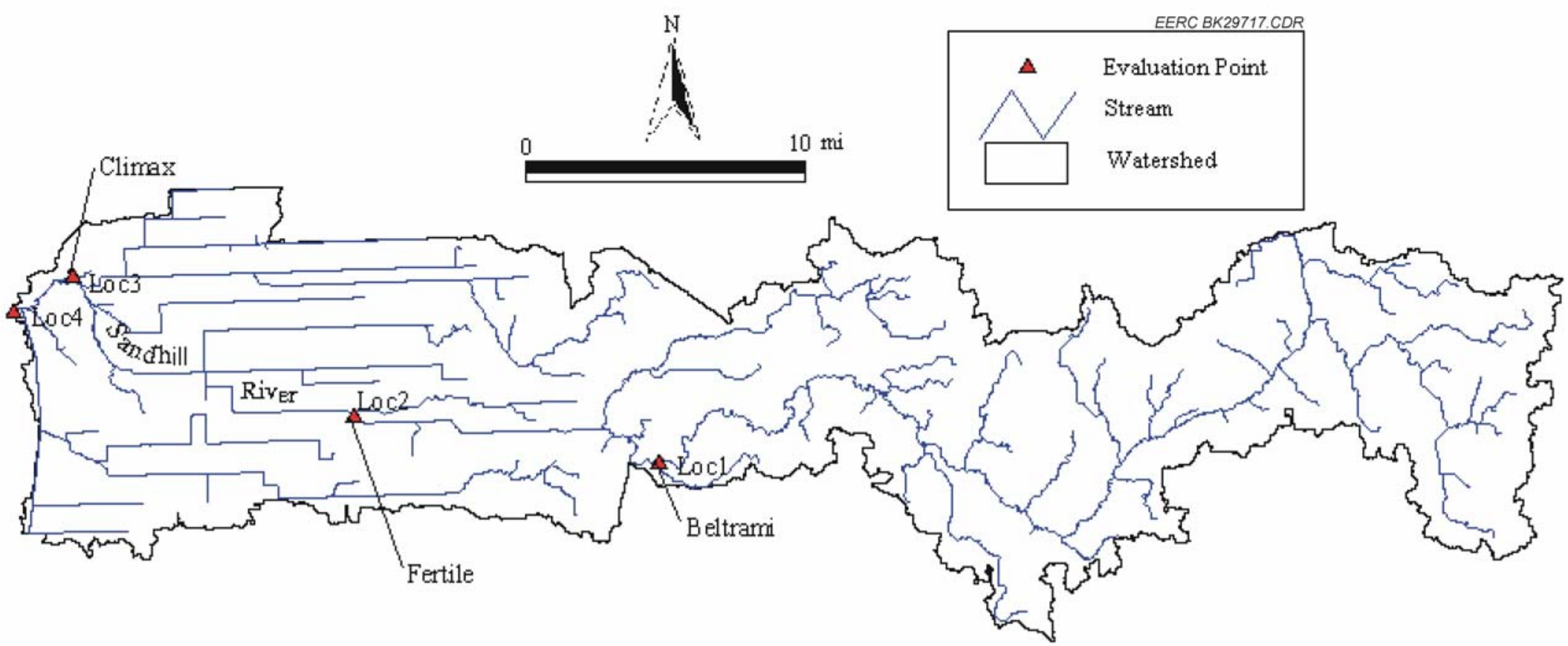


Figure C-25. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020301 (the Sandhill River Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-17.

Table C-18. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Red Lake, Thief, and Clearwater River Watersheds (HUC 09020303, 09020304, and 09020305), Shown in Figure C-27, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2			Loc3			Loc4		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	2290	2210	−3.5	4680	4330	−7.5	3365	3040	−9.7	2250	2180	−3.1
1979	3660	3605	−1.5	3230	2550	−21.1	3840	3720	−3.1	2060	2005	−2.7
1978	2225	2160	−2.9	2700	2460	−8.9	3070	2915	−5.0	2910	2825	−2.9
1975	2030	1950	−3.9	2740	2495	−8.9	2400	2190	−8.8	2095	2040	−2.6
1969	2195	2045	−6.8	3235	2890	−10.7	3520	3320	−5.7	3080	3010	−2.3
1966	3200	3135	−2.0	5260	4670	−11.2	1980	1720	−13.1	2670	2575	−3.6

	Loc5			Loc6			Loc7			Loc8		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	9340	8950	−4.2	24,600	23,670	−3.8	25,190	24,235	−3.8	20,070	19,090	−4.9
1979	9930	9575	−3.6	23,020	21,620	−6.1	25,680	24,090	−6.2	19,650	18,875	−3.9
1978	9960	9125	−8.4	15,640	14,650	−6.3	16,080	15,085	−6.2	13,000	12,140	−6.6
1975	7330	7090	−3.3	14,020	12,985	−7.4	16,210	14,935	−7.9	13,135	12,080	−8.0
1969	9000	8425	−6.4	27,275	25,570	−6.3	27,910	26,155	−6.3	20,590	19,185	−6.8
1966	8840	8395	−5.0	19,765	18,655	−5.6	21,650	20,425	−5.7	17,830	16,785	−5.9

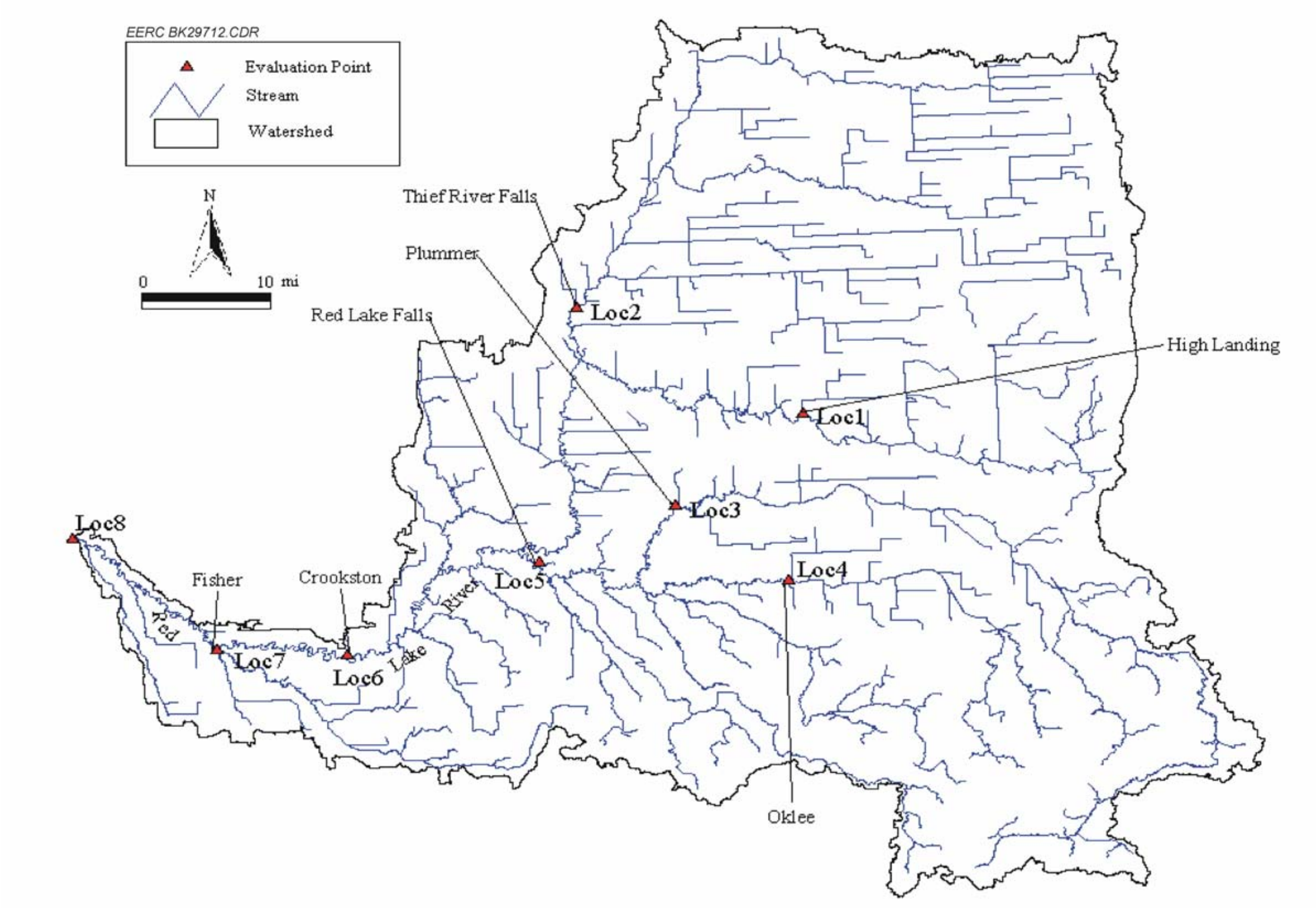


Figure C-26. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020303, 09020304, and 09020305 (the Red Lake, Thief, and Clearwater River Watersheds). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-18.

Table C-19. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Grand Marais River Watershed (HUC 09020306), Shown in Figure C-28, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2			Loc3			Loc4		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	195	125	−35.9	540	295	−45.4	680	385	−43.4	95	95	0.0
1979	110	70	−36.4	290	125	−56.9	360	185	−48.6	30	30	0.0
1978	25	15	−40.0	85	45	−47.1	95	55	−42.1	10	10	0.0
1975	45	30	−33.3	100	50	−50.0	130	75	−42.3	40	40	0.0
1969	90	60	−33.3	265	140	−47.2	310	175	−43.5	30	30	0.0
1966	15	15	0.0	30	15	−50.0	75	70	−6.7	115	115	0.0

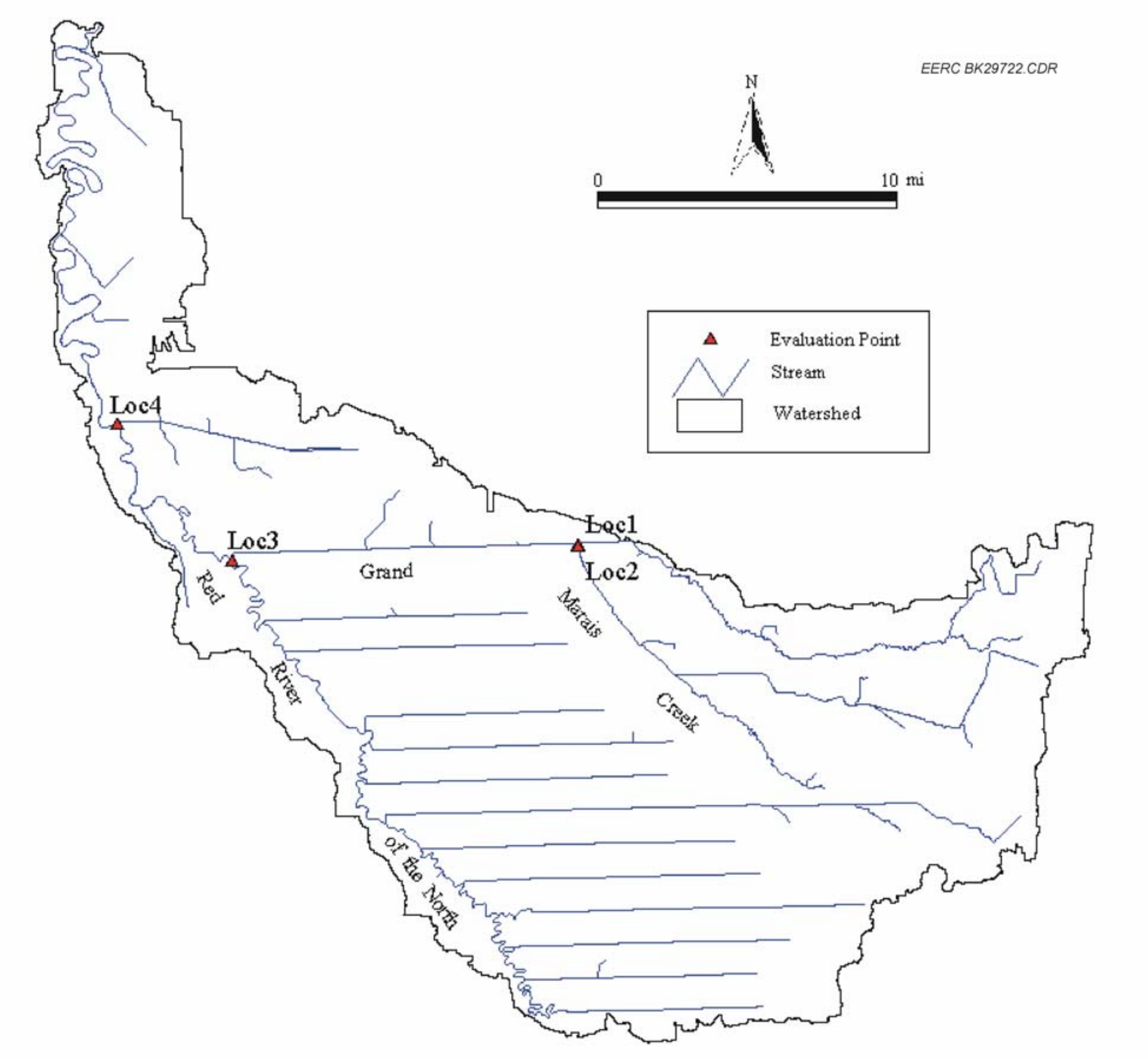


Figure C-27. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020306 (the Grand Marais River watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-19.

Table C-20. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Snake River Watershed (HUC 09020309), Shown in Figure C-29, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2			Loc3		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	2425	2275	−6.2	3795	3590	−5.4	2755	2520	−8.5
1979	1070	950	−11.2	1970	1790	−9.1	2695	2600	−3.5
1978	1050	950	−9.5	1345	1230	−8.6	1175	920	−21.7
1975	615	555	−9.8	935	860	−8.0	775	620	−20.0
1969	1630	1470	−9.8	2320	2140	−7.8	1890	1490	−21.2
1966	970	875	−9.8	1305	1190	−8.8	1055	850	−19.4

	Loc4			Loc5			Loc5		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	4060	3990	−1.7	500	485	−3.0	14,480	13,835	−4.5
1979	3140	3115	−0.8	575	565	−1.7	11,995	11,705	−2.4
1978	1450	1400	−3.4	215	205	−4.7	4925	4450	−9.6
1975	965	930	−3.6	140	135	−3.6	3420	3090	−9.6
1969	2535	2445	−3.6	340	330	−2.9	8655	7840	−9.4
1966	1320	1270	−3.8	190	185	−2.6	4765	4295	−9.9

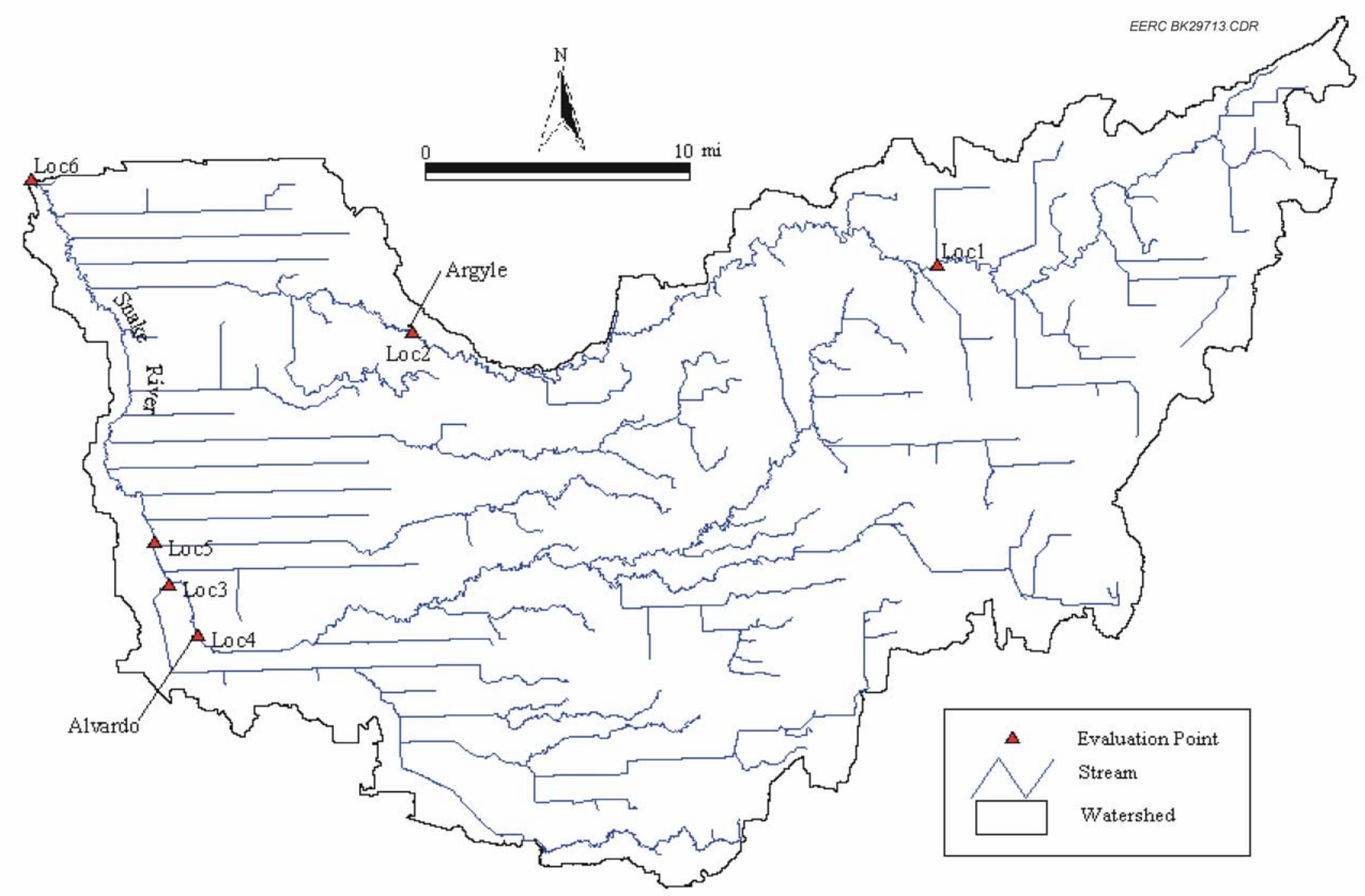


Figure C-28. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020309 (the Snake River Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-20.

Table C-21. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Lower Red River Watershed (HUC 09020311), Shown in Figure C-30, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2			Loc3			Loc4		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	4210	3485	−17.2	4700	3840	−18.3	5920	4955	−16.3	6085	5100	−16.2
1979	3600	3070	−14.7	4090	3405	−16.7	5110	4200	−17.8	5190	4260	−17.9
1978	2750	2150	−21.8	3120	2340	−25.0	3700	2815	−23.9	3785	2895	−23.5
1975	2320	1790	−22.8	2615	1950	−25.4	2945	2230	−24.3	3035	2315	−23.7
1969	2805	2130	−24.1	3140	2320	−26.1	4095	3115	−23.9	4155	3195	−23.1
1966	1945	1505	−22.6	2200	1650	−25.0	2400	1830	−23.8	2475	1905	−23.0

	Loc5			Loc6			Loc7			Loc8		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	470	380	−19.1	220	130	−40.9	2145	1620	−24.5	970	840	−13.4
1979	430	350	−18.6	195	110	−43.6	1925	1470	−23.6	895	745	−16.8
1978	300	230	−23.3	135	75	−44.4	1500	1005	−33.0	705	540	−23.4
1975	255	195	−23.5	115	70	−39.1	1315	890	−32.3	610	475	−22.1
1969	315	245	−22.2	145	85	−41.4	1590	1090	−31.4	740	575	−22.3
1966	215	165	−23.3	95	60	−36.8	1140	780	−31.6	535	415	−22.4

	Loc9			Loc10			Loc11			Loc12		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	2120	1695	−20.0	3345	2735	−18.2	35	25	−28.6	10	10	0.0
1979	1970	1510	−23.4	2970	2450	−17.5	150	110	−26.7	35	35	0.0
1978	1505	1105	−26.6	2345	1725	−26.4	40	30	−25.0	10	10	0.0
1975	1290	950	−26.4	2060	1520	−26.2	45	35	−22.2	10	10	0.0
1969	1510	1115	−26.2	2490	1855	−25.5	55	40	−27.3	15	15	0.0
1966	1110	825	−25.7	1795	1330	−25.9	60	45	−25.0	15	15	0.0

	Loc13			Loc14			Loc15			Loc16		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	265	185	−30.2	375	290	−22.7	130	125	−3.8	545	455	−16.5
1979	980	715	−27.0	1395	1105	−20.8	545	515	−5.5	2085	1765	−15.3
1978	245	175	−28.6	345	270	−21.7	130	125	−3.8	515	430	−16.5
1975	305	215	−29.5	425	335	−21.2	155	150	−3.2	620	525	−15.3
1969	385	270	−29.9	540	420	−22.2	190	180	−5.3	775	655	−15.5
1966	425	295	−30.6	600	465	−22.5	205	195	−4.9	860	720	−16.3

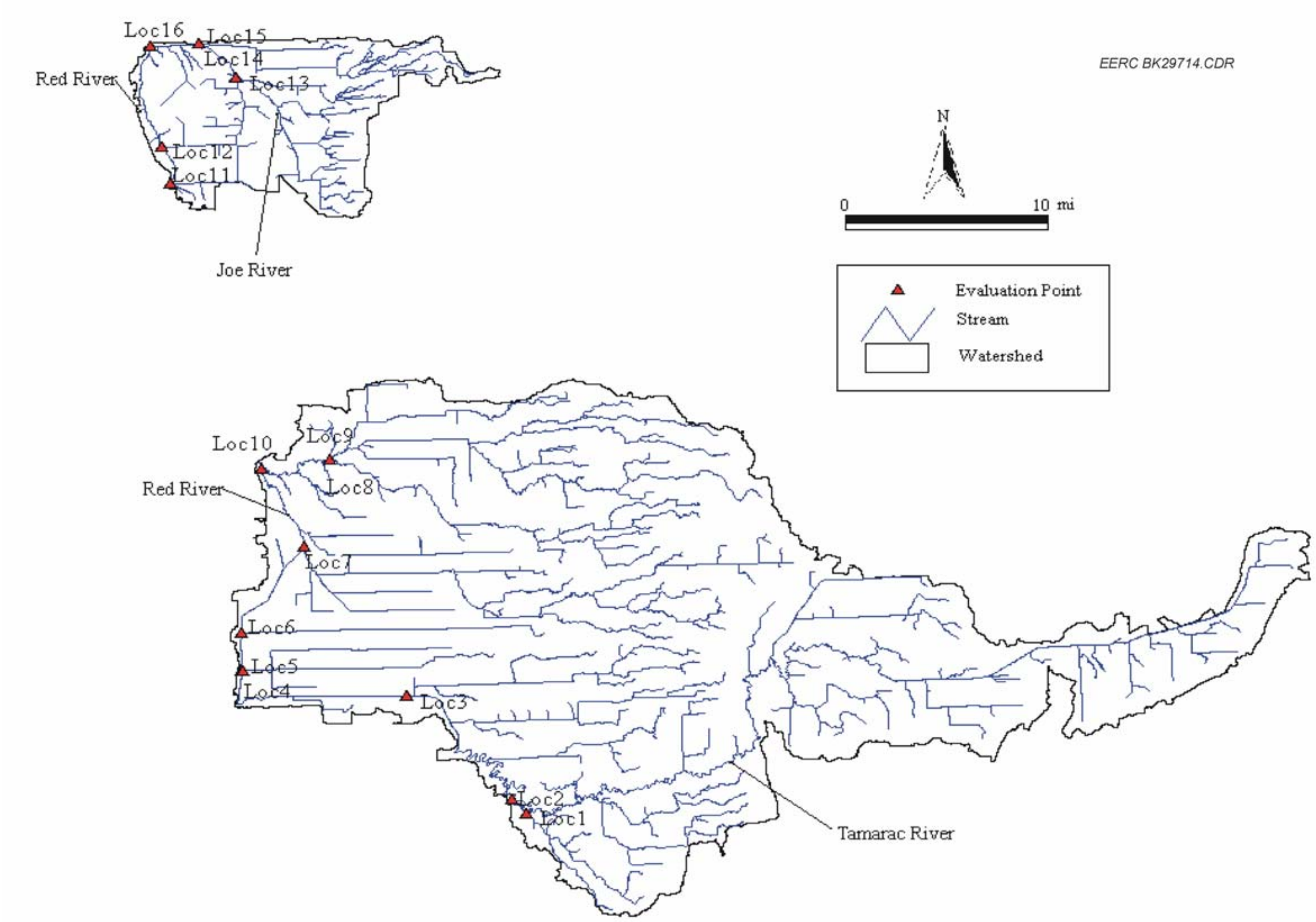


Figure C-29. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020311 (the Lower Red River Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-20.

Table C-22. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Two Rivers Watershed (HUC 09020312), Shown in Figure C-31, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc1			Loc2			Loc3			Loc4		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	4145	3695	−10.9	3840	3400	−11.5	510	420	−17.6	4790	4105	−14.3
1979	3145	2760	−12.2	3015	2630	−12.8	1165	1110	−4.7	6550	6090	−7.0
1978	2605	2175	−16.5	2420	2020	−16.5	665	640	−3.8	4095	3780	−7.7
1975	1875	1570	−16.3	1720	1430	−16.9	435	420	−3.4	2175	2035	−6.4
1969	2100	1760	−16.2	1920	1600	−16.7	620	605	−2.4	2980	2820	−5.4
1966	2095	1795	−14.3	1935	1655	−14.5	610	580	−4.9	3230	3060	−5.3
	Loc5			Loc6			Loc7			Loc8		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	1520	1230	−19.1	295	290	−1.7	60	55	−8.3	4775	4100	−14.1
1979	2255	2125	−5.8	1020	1005	−1.5	195	195	0.0	6595	6175	−6.4
1978	1395	1285	−7.9	610	595	−2.5	110	110	0.0	4180	3895	−6.8
1975	850	810	−4.7	430	420	−2.3	85	85	0.0	2210	2070	−6.3
1969	1180	1135	−3.8	605	590	−2.5	120	120	0.0	3005	2855	−5.0
1966	1090	1045	−4.1	535	520	−2.8	100	95	−5.0	3255	3090	−5.1

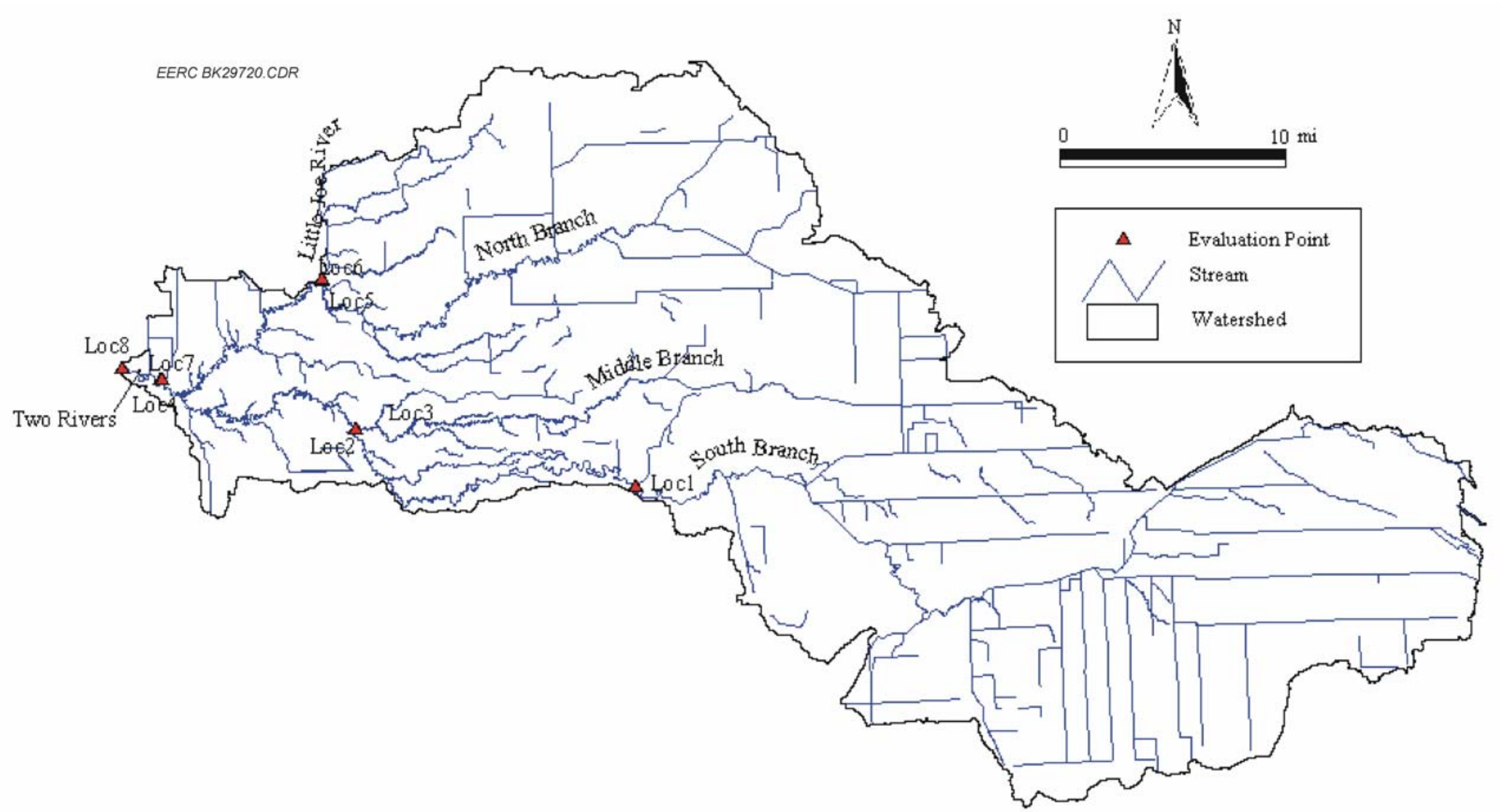


Figure C-30. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020312 (the Two Rivers Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-22.

Table C-23. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Roseau River Watershed (HUC 09020314), Shown in Figure C-32, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

		Loc1	
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	4315	4120	−4.5
1979	5245	4875	−7.1
1978	2570	2230	−13.2
1975	3560	3285	−7.7
1969	4645	4230	−8.9
1966	4365	3875	−11.2

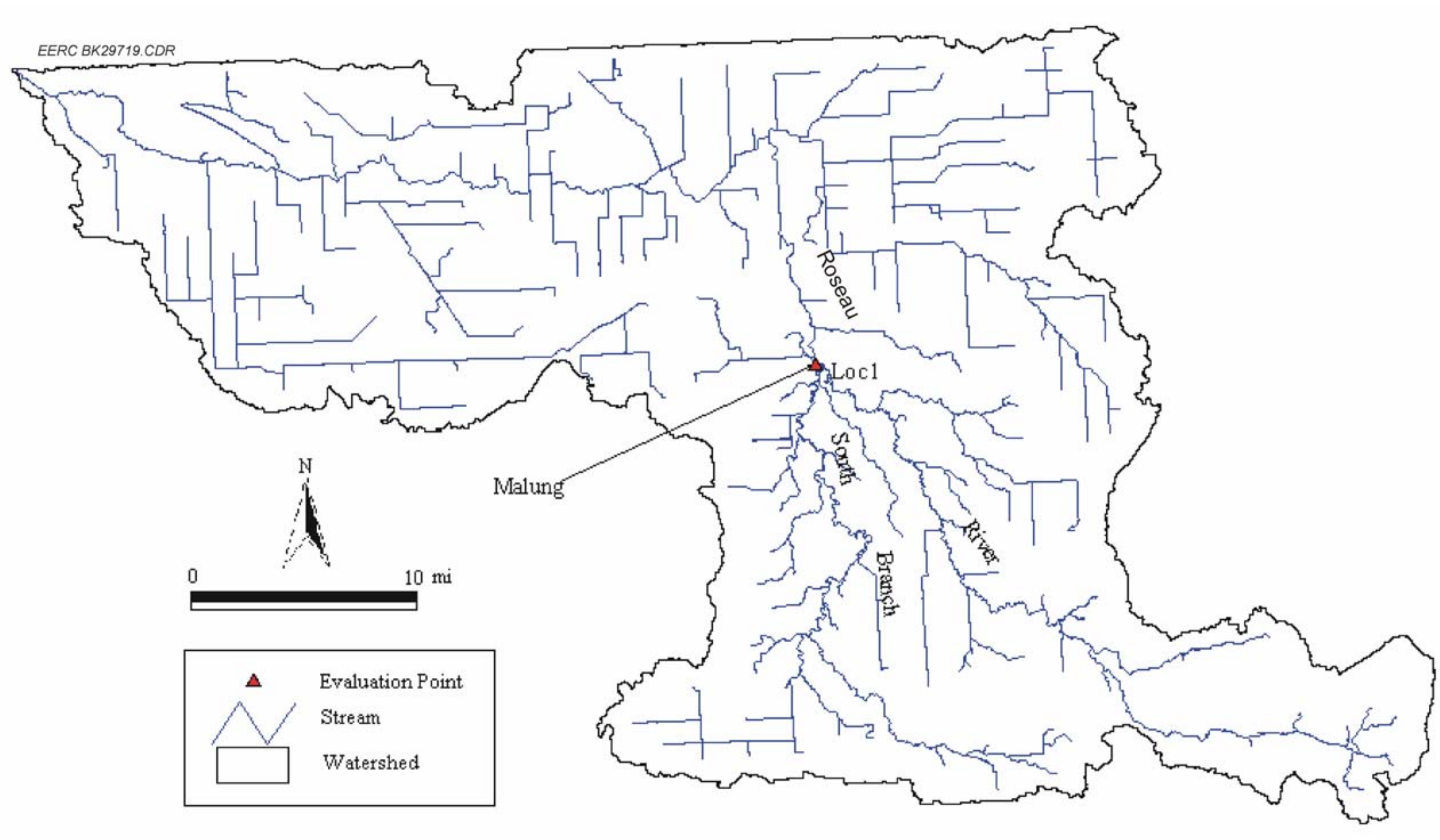


Figure C-31. Map showing the selected points of interest in the Minnesota modeling domain of HUC 09020314 (the Roseau River Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-23.

Table C-24. SWAT-Predicted Peak Flow Reductions at Selected Points of Interest Within the Elm River Watershed (HUC 09020107), Shown in Figure C-33, as a Result of Implementing Waffle Storage Scenario I for Various Historical Floods

	Loc 1			Loc 2			Loc 3		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, Cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	660	600	−9.1	735	670	−8.8	825	710	−13.9
1979	215	205	−4.7	570	515	−9.6	1135	955	−15.9
1978	535	495	−7.5	230	210	−8.7	1025	870	−15.1
1975	235	220	−6.4	355	320	−9.9	745	640	−14.1
1969	840	785	−6.5	550	495	−10.0	1330	1135	−14.7
1966	140	130	−7.1	210	185	−11.9	595	505	−15.1

	Loc 4			Loc 5			Loc 6		
Flood Event	Pre-Waffle (cfs)	S-I (cfs)	Reduction (%)	Pre-Waffle (cfs)	S-I (cfs)	Reduction (%)	Pre-Waffle (cfs)	S-I (cfs)	Reduction (%)
1997	2215	1875	−15.3	1675	1125	−32.8	2140	1805	−15.7
1979	1225	915	−25.3	1335	910	−31.8	1175	885	−24.7
1978	1080	935	−13.4	1340	910	−32.1	1095	960	−12.3
1975	680	595	−12.5	1335	910	−31.8	680	565	−16.9
1969	2185	1835	−16.0	1335	910	−31.8	2100	1785	−15.0
1966	670	525	−21.6	1335	910	−31.8	640	510	−20.3

	Loc 7			Loc 8			Loc 9		
Flood Event	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %	Pre-Waffle, cfs	S-I, cfs	Reduction, %
1997	930	610	−34.4	3985	2925	−26.6	4885	3460	−29.2
1979	945	660	−30.2	2490	1675	−32.7	3460	2245	−35.1
1978	880	655	−25.6	1425	1140	−20.0	1955	1495	−23.5
1975	540	405	−25.0	1505	1065	−29.2	1675	1120	−33.1
1969	1335	965	−27.7	3730	2620	−29.8	5115	3445	−32.6
1966	520	395	−24.0	1390	960	−30.9	1570	1015	−35.4

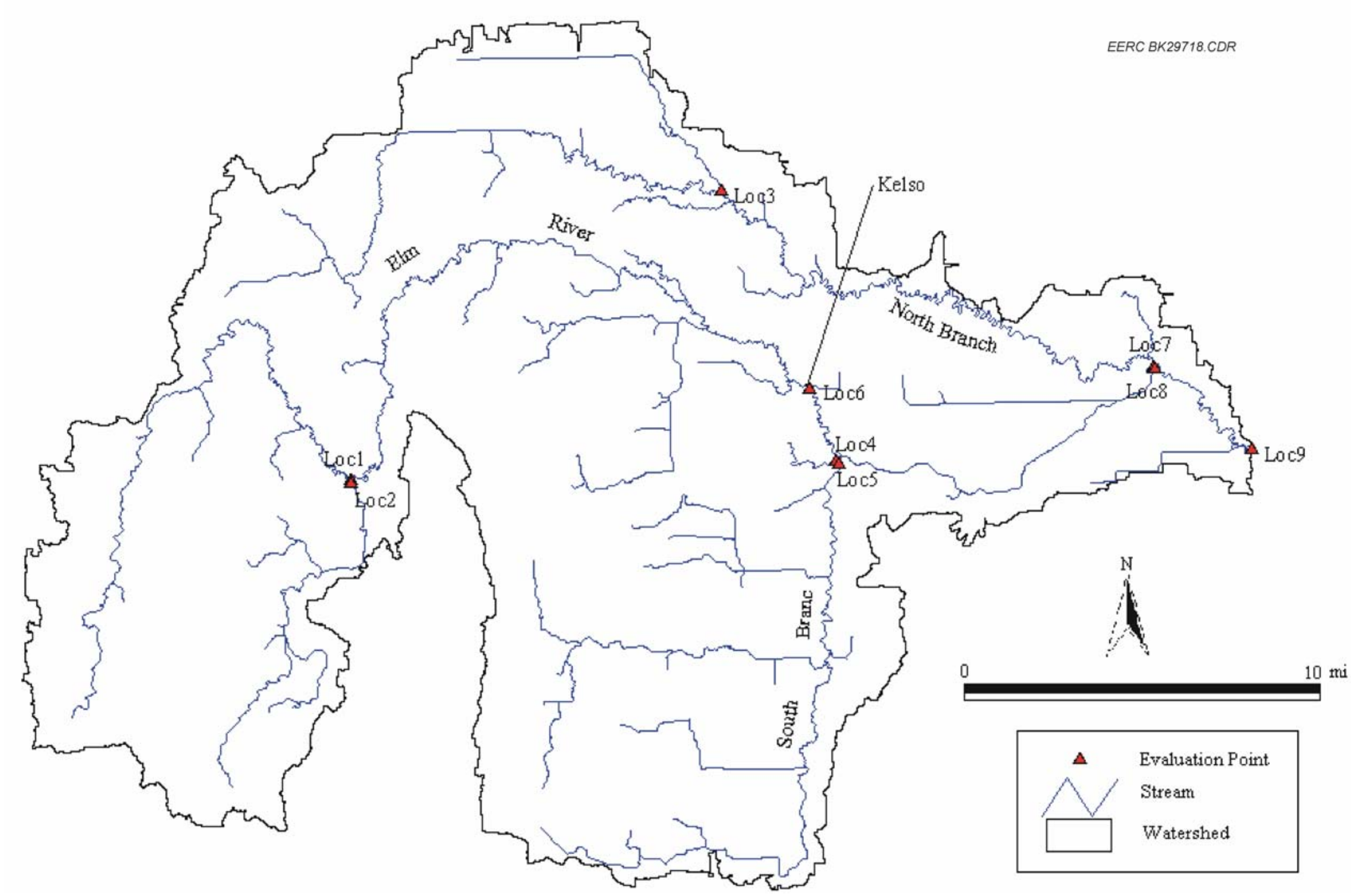


Figure C-32. Map showing the selected points of interest in the North Dakota modeling domain of HUC 09020107 (the Elm River Watershed). The predicted peak flow reductions at these points as a result of implementing Waffle Scenario I for historical floods are presented in Table C-24.

(Table 10). The reduction effect of Waffle storage is likely to become smaller for flood events with a prolonged rising limb because the water prior to the peak tends to fill the storage areas, reducing the storage volume available for regulating the peak.

SUMMARY

This study evaluated three Waffle scenarios. Scenario I (S-I) modeled 100% of the identified storage, whereas Scenario II (S-II) and Scenario III (S-III) modeled 75% and 50% of the identified storage, respectively. The evaluation was conducted for each of the 25 modeling domains or watersheds. For each of the 13 Minnesota watersheds, an additional evaluation was implemented for six historical floods that occurred in 1966, 1969, 1975, 1978, 1979, and 1997.

The predicted Waffle effects were measured as peak flow reductions at each watershed outlet during a 1997-type event. An additional assessment was also conducted to determine the Waffle storage effects during a 1997-type flood at several points of interest (i.e., selected evaluation locations) within the Minnesota watersheds and for the Elm River Watershed (modeling domain HUC 09020107).

In the SWAT models, the Waffle storage was modeled as “synthetic” ponds. To accomplish this, a new algorithm for defining a “synthetic” pond was established by this study. This algorithm ensured that the hydrologic function of the synthetic ponds was representative of Waffle storage areas.

The results indicated that for a given watershed, the effects of the Waffle storage would depend upon both the ratio of Waffle storage volume to watershed size as well as the width-to-length ratio. The percentage reductions are larger for watersheds with a greater storage-to-drainage area ratio and a greater width-to-length ratio. However, the spatial distribution of the storage areas within the watershed is also a factor that controls the reduction effect. When two watersheds have near-equivalent storage volumes, the Waffle would be more effective for the watershed with storage areas capable of controlling upland runoff rather than storage that intercepts concentrated stream flows. Because of the spatial variability of Waffle storage and the drainage network, the flood reduction effects at different locations within a watershed could be distinctly different. Further, the reduction effects would be smaller for a flood event with a large peak and/or a prolonged rising limb.

HEC–RAS MODEL

Data and Model Setup

In this study, two HEC–RAS hydrodynamic (unsteady-state) models were used to predict reductions of the 1997 flood crests along the Red River main stem. The first model, developed by Mr. Stuart Dobberpuhl, a hydraulic engineer from the USACE St. Paul District, covers the reach from White Rock to Halstad (Figure C-33). The second model, developed by the EERC, includes the reach from Halstad to Emerson (Figure C-34). The outputs from the first model

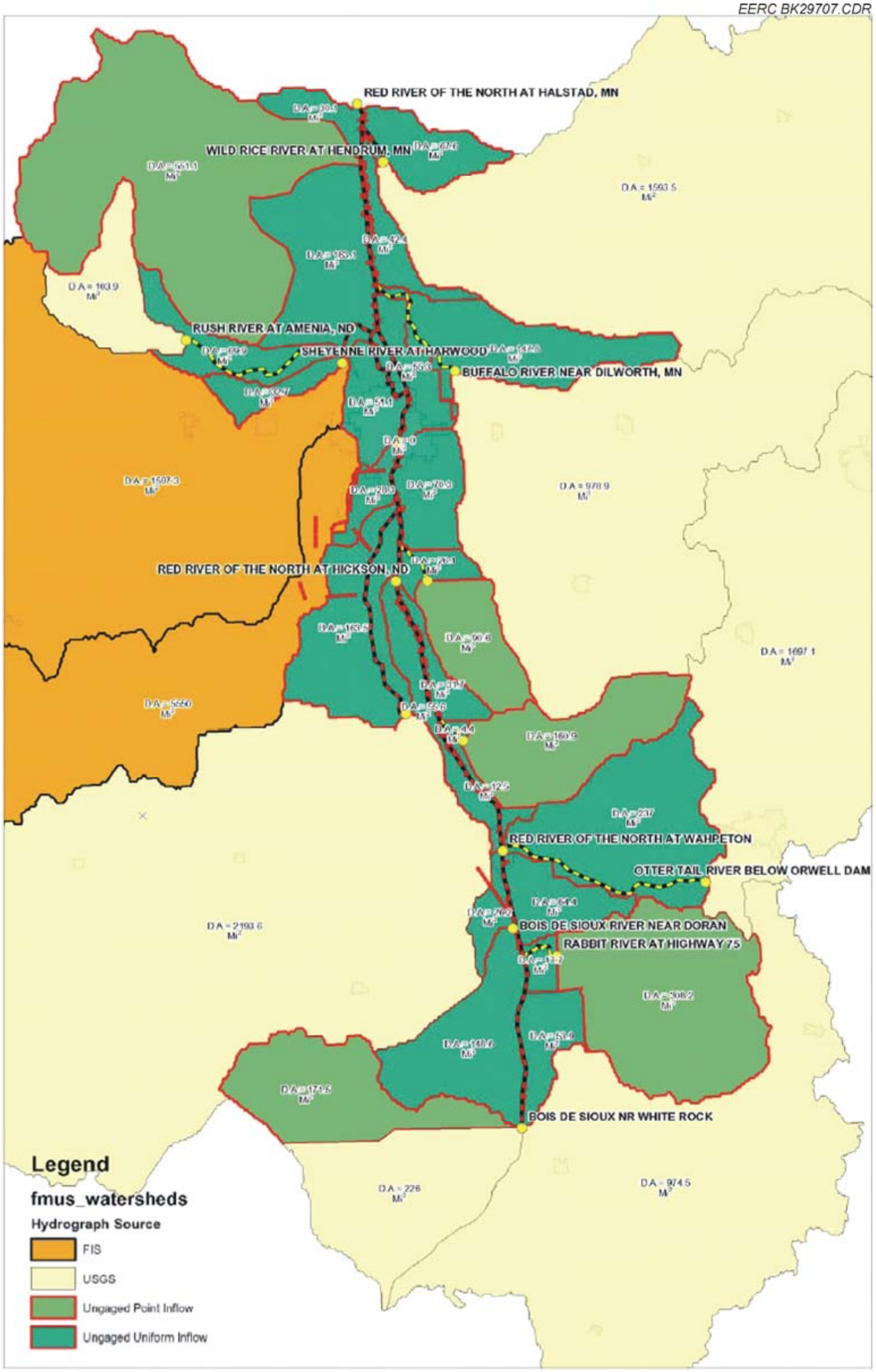


Figure C-33. Schematic of the HEC–RAS model for the Red River main stem from White Rock to Halstad.

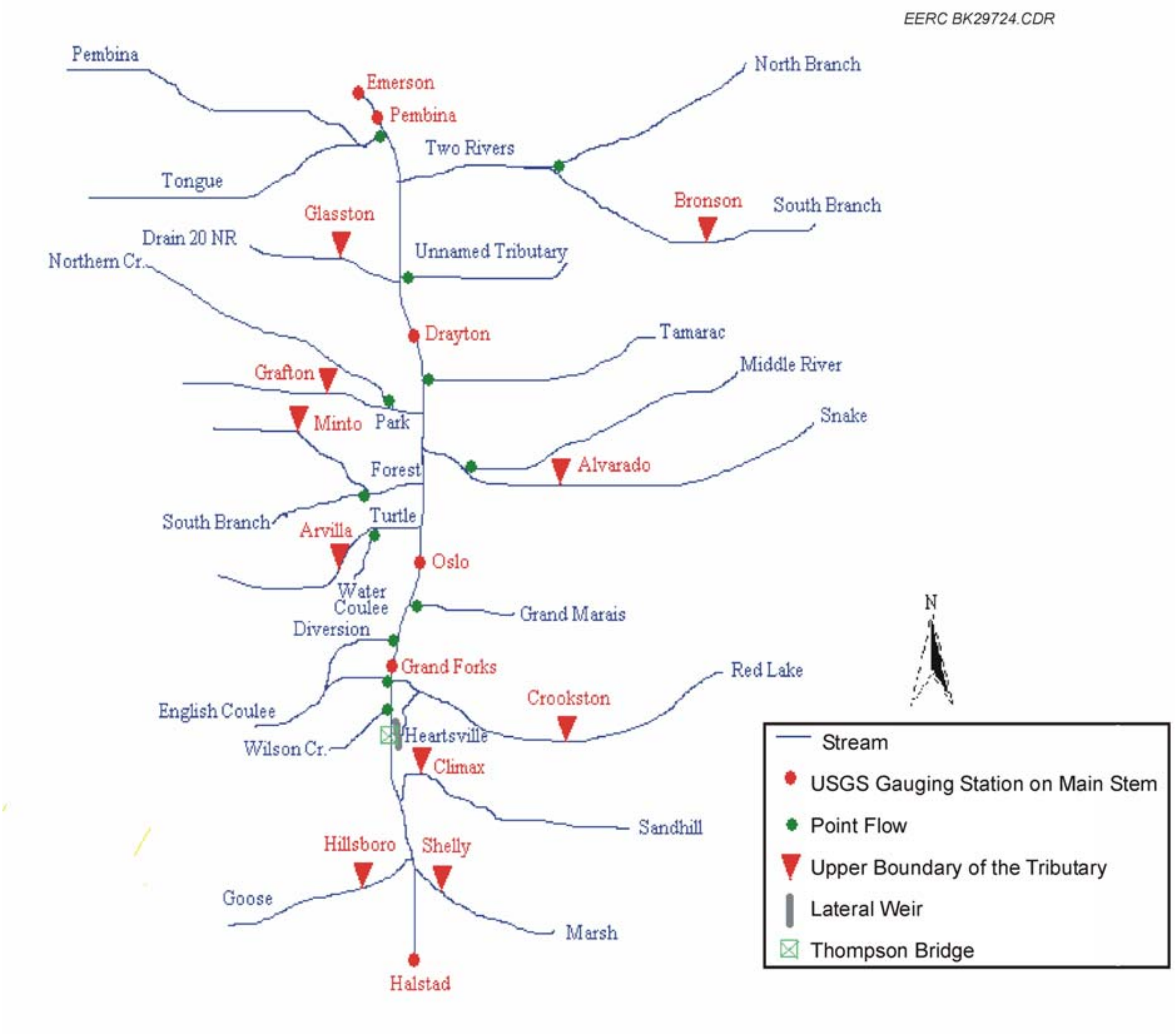


Figure C-34. Schematic of the HEC–RAS model for the Red River main stem from Halstad to Emerson.

were used as the inputs into the second model, enabling a seamless prediction along the main stem from White Rock to Emerson. For description purposes, hereinafter, the first model is designated “ACE-M,” whereas the second model is designated “EERC-M.” The common features of these two models are that 1) the flows simulated by the aforementioned SWAT models were used to define the boundary conditions when the USGS observed data were unavailable; 2) the flows from the ungauged drainage areas (i.e., areas that contribute flow that is not measured by any USGS gauging station) were simulated by the SWAT models; 3) the major tributaries were explicitly modeled; 4) all bridges and major breakout flows, such as that which occurred along the Maple and Sheyenne Rivers and at the Thompson Bridge, were considered; 5) all available cross-sectional data for the main stem Red River were used; and 6) the models incorporated the best knowledge of the engineers, including Mr. Scott Jutila, Mr. Randy Gjestvang, Mr. James Fay, Mr. Stuart Dobberpuhl, and Mr. Michael Lesher, to name a few.

The geometric data for the cross sections and bridges along the Red River main stem were extracted from the HEC–RAS steady-state model that was distributed with the USACE's "Regional Red River Flood Assessment Report," dated January 2003. In addition, the cross-sectional data for the tributaries that were modeled in ACE-M were generated using the USGS 1:24,000 quadrangle maps or extracted from a HEC–RAS unsteady-state model developed by the Pacific International Engineering for the "Maple River and Overflow Area Flood Insurance Study." Details on ACE-M can be found in the final report for the USACE's "Fargo–Moorhead Upstream Feasibility Study" project, entitled "Hydrology and Hydraulics Analysis."

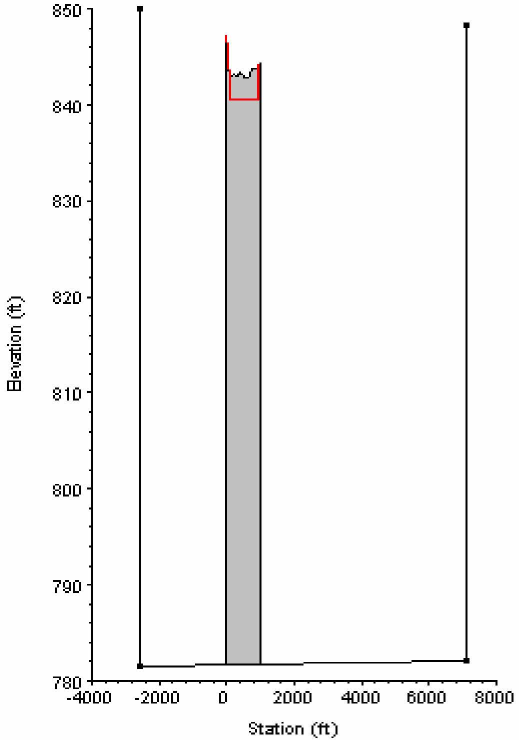
Table C-25 presents the tributary-modeling approach used in EERC-M. The geometric data for the Red Lake River and Heartsville Coulee were extracted from the HEC–RAS steady-state models provided by Mr. Michael Lesher, a hydraulic engineer from USACE. These data reflect the current topography with the levees along the Red Lake River and the Heartsville Diversion channel constructed. The new bridge crossing the Hartsville Coulee Diversion channel was also included in the model. The cross sections for the other tributaries that were modeled as a branch were generated using the topographic information provided by the NED data. The flows for the upper and lateral boundary conditions and at the inflow points were simulated by the corresponding SWAT models. The Red River main stem was modeled as ten subreaches to account for the hydraulic connections between the Red River and the modeled tributaries. These subreaches were described by 248 cross sections that were extracted from the HEC–RAS steady-state model distributed with the USACE's "Regional Red River Flood Assessment Report," dated January 2003. The cross sections for the subreach affected by the Grand Forks–East Grand Forks Dike Project were taken from a steady-state HEC–RAS model, developed and used by USACE to update the Grand Forks–East Grand Forks Flood Insurance Rating Map, to reflect the current ground-truth conditions. In addition, EERC-M included 19 bridges crossing the Red River main stem. One lateral weir was added at Thompson Bridge to model the overflow from the Red River into the Heartsville Coulee. The data used to define the lateral weir were provided by Mr. Michael Lesher and are presented in Table C-26. The upper boundary condition of EERC-M was specified as the flow hydrograph at Halstad (USGS 05064500), whereas the lower boundary condition was defined as a normal depth with a friction slope of 0.000065, determined based on the elevation information provided in the geometric data for the cross sections at, and adjacent to, Emerson, Manitoba (USGS 05102500).

As with ACE-M, EERC-M was also calibrated in accordance with the 1997 flood. The calibration was conducted with the goal of closely matching simulated daily stream flow hydrographs to the corresponding observed hydrographs at Drayton, Pembina, and Emerson. The observed flow hydrograph at Grand Forks was not used for the model calibration because the Grand Forks–East Grand Forks Dike Project has noticeably changed the topography and geomorphology of the subreach located within the city limits. Given these changes, a hydrologic condition that is identical to that of 1997 would result in a distinctly different flow hydrograph. In order to evaluate the effects of proposed flood mitigation projects (i.e., the Waffle) on flood crest reductions, the geometric data for the current ground truth conditions (i.e., the topography with the dikes and diversions constructed) rather than the 1997 geomorphology should be used to

Table C-25. Tributaries Included in the HEC–RAS Non-Steady-State Model for the Red River Main Stem from Halstad to Emerson

Tributary	Modeling Approach	Boundary Conditions			Number of Cross Section
		Upper	Lower	Middle	
Marsh	Branch	Flow at Shelly (USGS 05067500)	Junction with RR	Lateral flow	5
Sandhill	Branch	Flow at Climax (USGS 05069000)	Junction with RR	Lateral flow	4
Red Lake	Branch	Flow at Crookston (USGS 05079000)	Junction with RR	Lateral flow	35
Heartsville Coulee	Branch	Lateral weir at Thompson Bridge	Junction with Red Lake	Uniform lateral flow	69
Grand Marais	Point flow into RR	–	–	–	–
Snake	Branch	Flow at Alvarado (USGS 05085900)	Junction with RR	Lateral flow	7
Middle River	Point flow into Snake	–	–	–	–
Tamarac	Point flow into RR	–	–	–	–
Unnamed Tributary	Point flow into RR	–	–	–	–
Two Rivers	Branch	Flow at Bronson (USGS 05094000)	Junction with RR	Lateral flow	7
North Branch	Point flow into Two Rivers	–	–	–	
Goose	Branch	Flow at Hillsboro (USGS 05066500)	Junction with RR	Lateral flow	7
English Coulee	Point flow into RR	–	–	–	–
Diversion	Point flow into RR	–	–	–	–
Turtle	Branch	Flow at Arvilla (USGS 05082625)	Junction with RR	Lateral flow	8
Water Coulee	Point flow into Turtle	–	–	–	–
Forest	Branch	Flow at Minto (USGS 05085000)	Junction with RR	Lateral flow	8
South Branch	Point flow into Forest	–	–	–	–
Park	Branch	Flow at Grafton (USGS 05090000)	Junction with RR	Lateral flow	8
Northern Creek	Point flow into Park	–	–	–	–
Drain 20 NR	Branch	Flow at Glasston (USGS 05092200)	Junction with RR	Lateral flow	4
Pembina	Point flow into RR	–	–	–	–
Tongue River	Point flow into Pembina	–	–	–	–

Table C-26. Data Used to Define the Lateral Weir at Thompson Bridge

Station, ft	Distance, ft	Sketch Graph and Remark
0.00	847.09	 The lateral weir was modeled to have a breach bottom width of 800 ft with a side slope of 5 and a breach bottom elevation of 840.5 ft. The breach was assumed to be a result of overtopping that starts at a water surface elevation of 842.87 ft.
1.00	847.00	
12.50	846.00	
34.00	845.00	
55.30	844.00	
59.20	843.82	
170.52	843.03	
214.50	843.22	
272.30	843.00	
324.70	843.05	
345.60	843.05	
397.00	843.35	
405.30	843.23	
432.30	843.19	
464.30	843.19	
500.80	843.04	
507.50	842.88	
543.30	842.87	
663.05	842.87	
693.30	842.98	
700.90	843.02	
749.90	843.72	
793.90	843.78	
852.00	843.85	
923.70	843.98	
954.20	843.98	
957.00	844.19	
972.70	844.32	
988.64	844.40	

set up the model. One may argue that the model should first be set up using the geometric data for the 1997 geomorphology and calibrated using the observed flow hydrograph. The cross sections for the subreach affected by the construction project would then be revised to represent the geometry of the current ground truth. This approach is logical for assessing the effects of the dike project, but less useful for evaluating the effects of other projects because the comparison should be made using current conditions. Thus, instead of this approach, the Manning's n values used to design the dikes and diversions were adopted for the cross sections of the subreach affected by the construction project. The model-simulated flow hydrograph was assumed to be the one corresponding to the 1997 hydrologic condition but with the current topography and geomorphology. This flow hydrograph was used as the comparison base to evaluate the effects of the Waffle. However, the observed flow hydrographs at stations downstream of Grand Forks were used to calibrate the model because USACE has shown that the changes in the Grand Forks–East Grand Forks Dike Project have a negligible influence on the flow regimes located 1 mile away from the northern boundary of the project (Mike Descher, USACE, personal communication, 2006).

The model calibration was achieved by manually adjusting the Manning's n values for individual cross sections. A key goal of the calibration was to achieve a close match between the simulated water surface elevation hydrographs and the corresponding observed hydrographs at Halstad, Drayton, Pembina, and Emerson. However, because it is infeasible to have best matches for both flow and elevation, the first priority of the calibration was an accurate simulation of flows.

As shown in Table C-27, EERC-M performed well in predicting both peaks and volumes. As expected, Halstad is the model upper boundary; thus, the predicted and observed values at this station are identical. The model successfully reproduced the peak discharges and timings at the three stations downstream of Grand Forks. The maximum prediction error is only off by 1.72%, or 1 day. In addition, the prediction error for volumes is less than 1%. The results for Grand Forks are presented for informational purposes only because this station was not used for model calibration. Nevertheless, the model performance is acceptable for Grand Forks as well. Further, the model predicted the daily discharge with sufficient accuracy, as indicated by R^2 values of 0.65 or greater and slopes nearing 1 (Figures C-35 to C-38). Also, the predicted stage hydrographs match well with the corresponding observed hydrographs (Figures C-39 to C-43). The observed stages were obtained from USACE. Again, the results for Grand Forks are shown for informational purposes only because this station was not used for model calibration. The model indicated that a peak discharge of 10,425 cfs might overtop the Thompson Bridge and flow into the Heartsville Coulee in 1997 (Figure C-44). Considering the flows generated in the area drained by the coulee, the discharge of 12,000 cfs used by USACE to design the Heartsville Diversion is very reasonable.

Table C-27. Observed and EERC-M Predicted Peaks and Volumes for the 1997 Flood

Station	Observed Peak		Predicted Peak		Volume (from April 14 to May 10		
	Magnitude, cfs	Timing	Magnitude, cfs	Timing	Observed, acre-ft	Predicted, acre-ft	Error, %
Halstad[1]	69,900	Apr 19	69,900	Apr 19	2,323,041	2,323,041	0.00
Grand Forks[2]	127,000	Apr 18	102,420	Apr 22	3,613,091	3,381,224	−6.42
Drayton	124,000	Apr 24	121,859	Apr 24	3,882,446	4,240,783	0.92
Pembina[3]	141,400	Apr 26	140,430	Apr 27	4,429,307	5,032,677	0.93
Emerson[4]	141,400	Apr 26	140,488	Apr 27	4,439,217	5,032,312	0.74

[1] As the model upper boundary, the predicted and observed values at this station are identical.

[2] The results are presented for information purposes only because the station was not used for model calibration.

[3] The observed flow hydrograph was derived by Dr. Xixi Wang, P.E., a research scientist at the EERC, University of North Dakota, using the data on observed stages and the rating curve provided by Mr. Steven Robinson from the USGS.

[4] The observed flow hydrograph was provided by Mr. Alf Warkentin from Manitoba Water Stewardship. This corrected hydrograph considered the overflows occurred at the west bank of the Red River of the North in the vicinity of Emerson. In contrast, the USGS data did not consider the overflows.

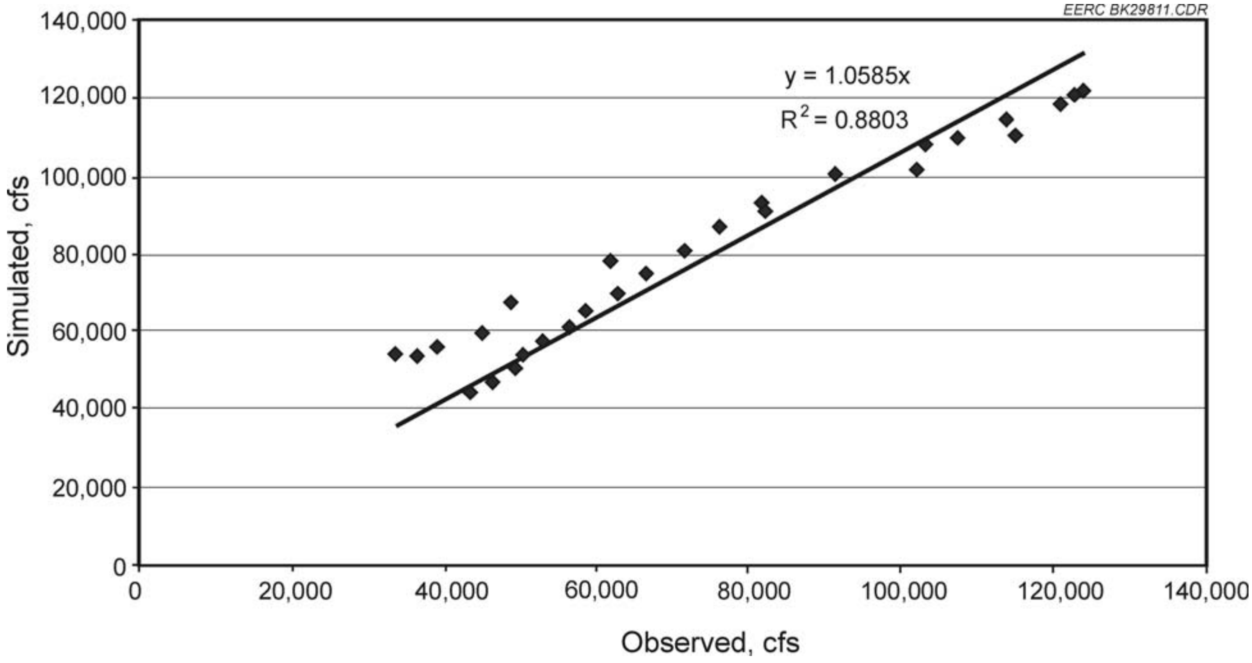


Figure C-35. Plot showing the simulated vs. observed daily discharges at Drayton.

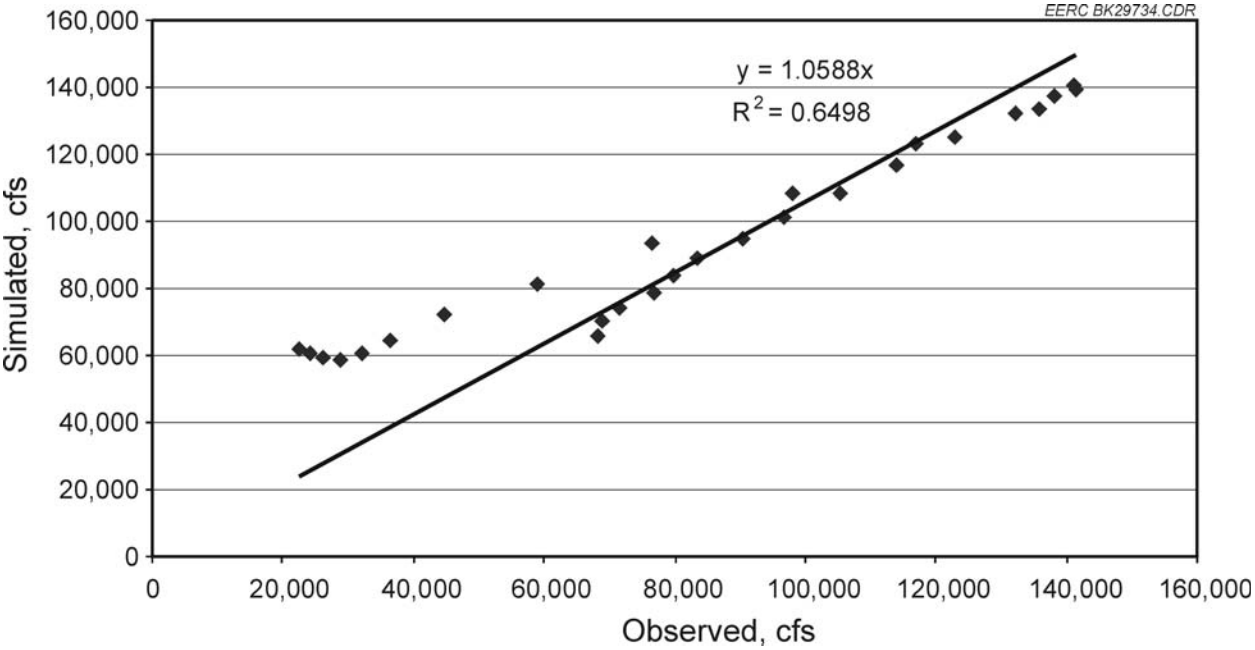


Figure C-36. Plot showing the simulated vs. observed daily discharges at Pembina.

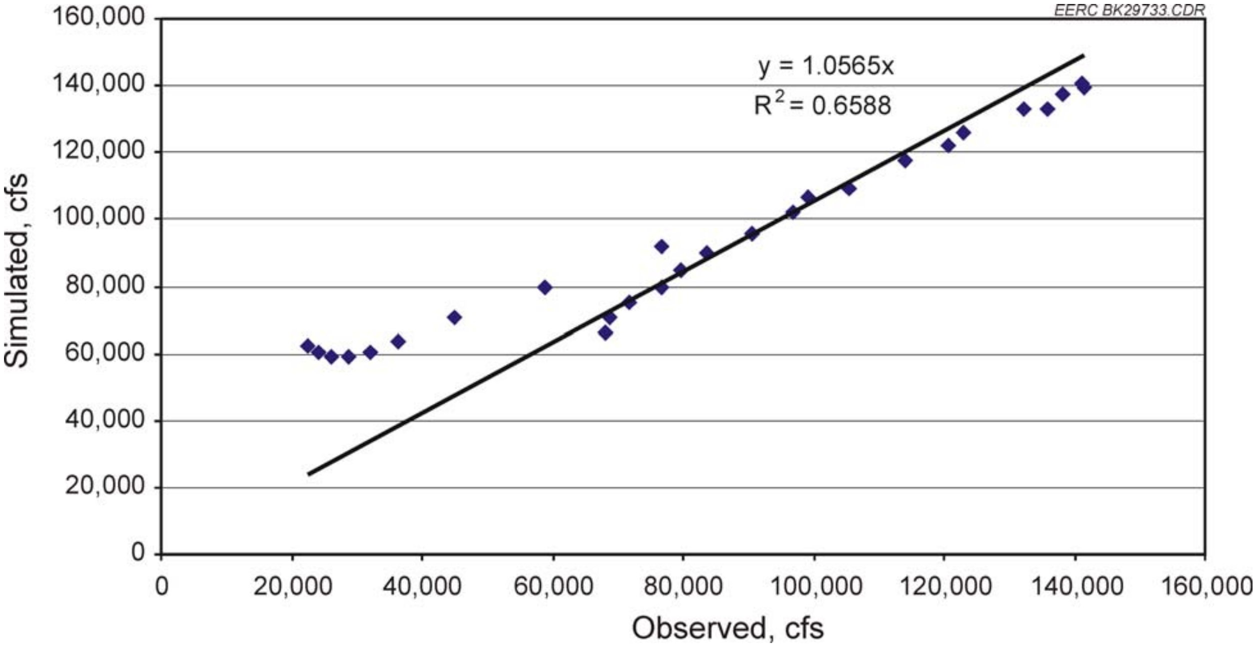


Figure C-37. Plot showing the simulated vs. observed daily discharges at Emerson.

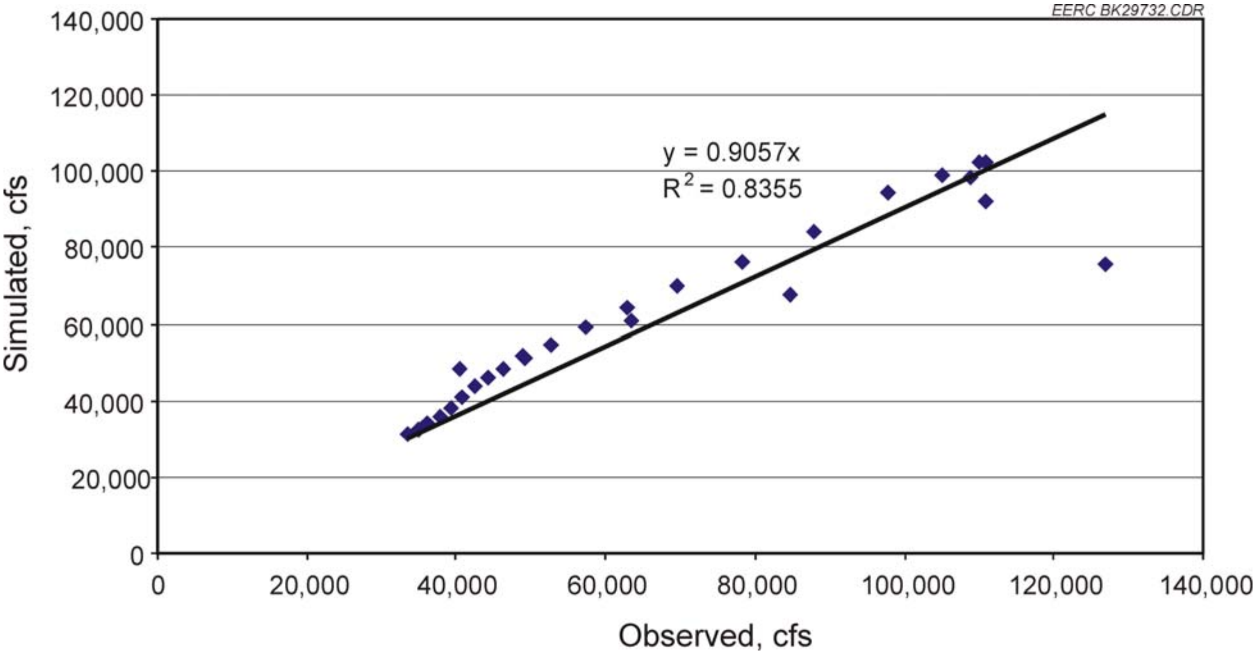
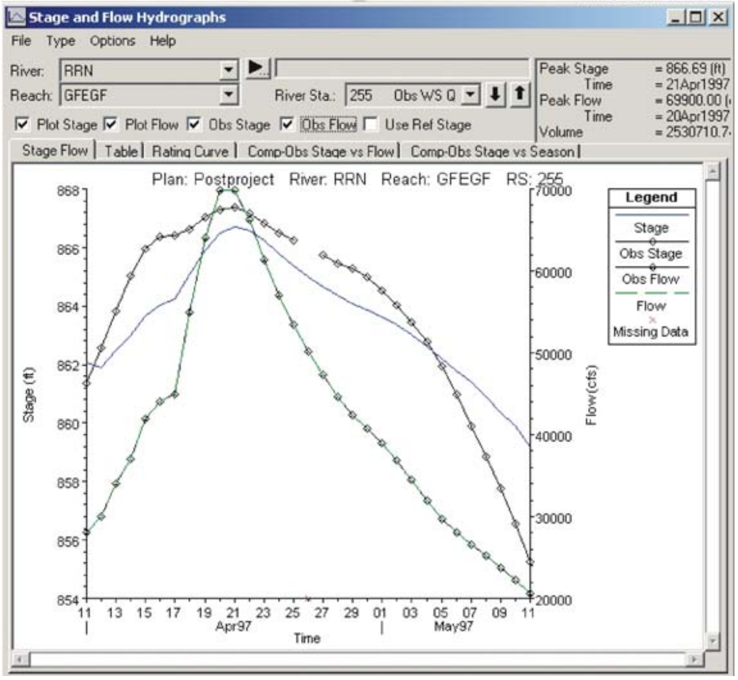


Figure C-38. Plot showing the simulated vs. observed daily discharges at Grand Forks. It should be noted that this station was not used for model calibration. The results are shown for informational purposes only.

EERC BK29701.CDR

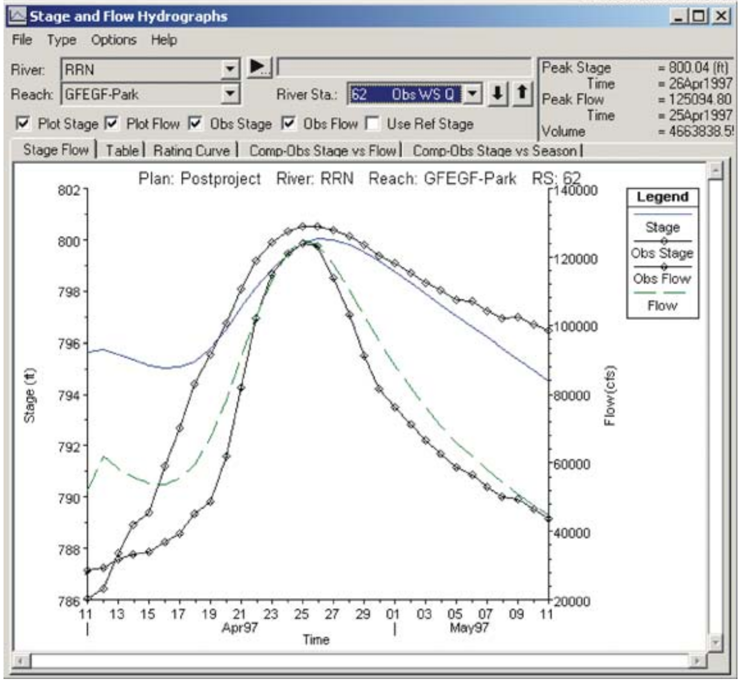


River: RRN
Reach: GFEGF
River Sta.: 255 Obs WS Q
☑ Plot Stage ☑ Plot Flow ☑ Obs Stage ☑ Obs Flow ☐ Use Ref Stage

Peak Stage = 866.69 (ft)
Time = 21Apr1997
Peak Flow = 69900.00 (
Time = 20Apr1997
Volume = 2530710.7

Figure C-39. Plot showing the observed and predicted discharges and water surface elevations at Halstad. The observed stages were obtained from USACE.

EERC BK29702.CDR

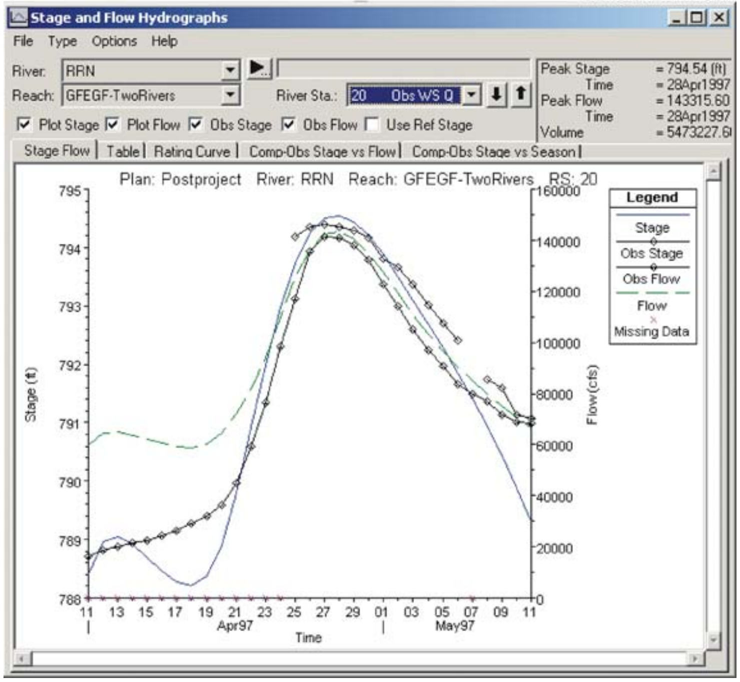


River: RRN
Reach: GFEGF-Park
River Sta.: 62 Obs WS Q
☑ Plot Stage ☑ Plot Flow ☑ Obs Stage ☑ Obs Flow ☐ Use Ref Stage

Peak Stage = 800.04 (ft)
Time = 26Apr1997
Peak Flow = 125094.80
Time = 25Apr1997
Volume = 4663838.5

Figure C-40. Plot showing the observed and predicted discharges and water surface elevations at Drayton. The observed stages were obtained from USACE.

EERC BK29703.CDR



River: RRN

Reach: GFEGF-TwoRivers

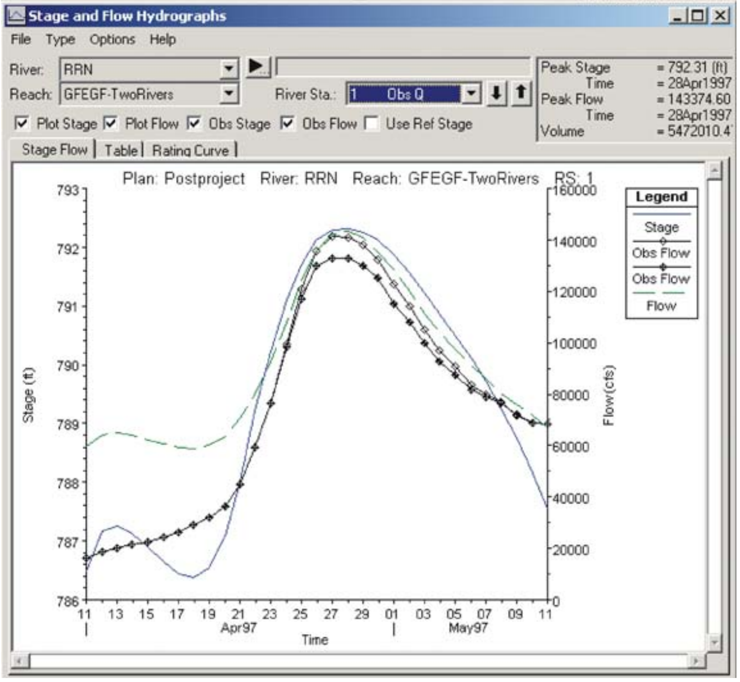
River Sta.: 20 Obs WS Q

☑ Plot Stage ☑ Plot Flow ☑ Obs Stage ☑ Obs Flow ☐ Use Ref Stage

Peak Stage = 794.54 (ft)
Time = 28Apr1997
Peak Flow = 143315.60
Time = 28Apr1997
Volume = 5473227.6

Figure C-41. Plot showing the observed and predicted discharges and water surface elevations at Pembina. The observed stages were obtained from USGS.

EERC BK29704.CDR



River: RRN

Reach: GFEGF-TwoRivers

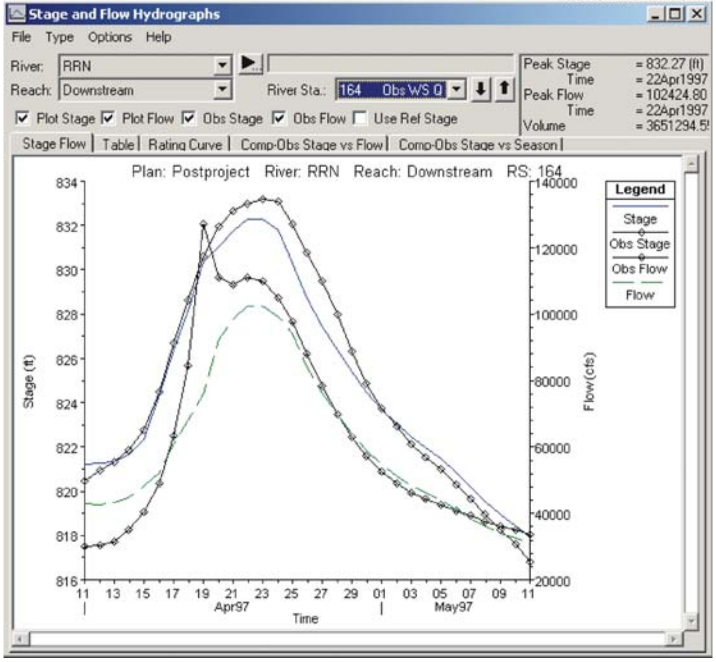
River Sta.: 1 Obs Q

☑ Plot Stage ☑ Plot Flow ☑ Obs Stage ☑ Obs Flow ☐ Use Ref Stage

Peak Stage = 792.31 (ft)
Time = 28Apr1997
Peak Flow = 143374.60
Time = 28Apr1997
Volume = 5472010.4

Figure C-42. Plot showing the observed and predicted discharges and water surface elevations at Emerson. The observed stages were obtained from USACE.

EERC BK29705.CDR

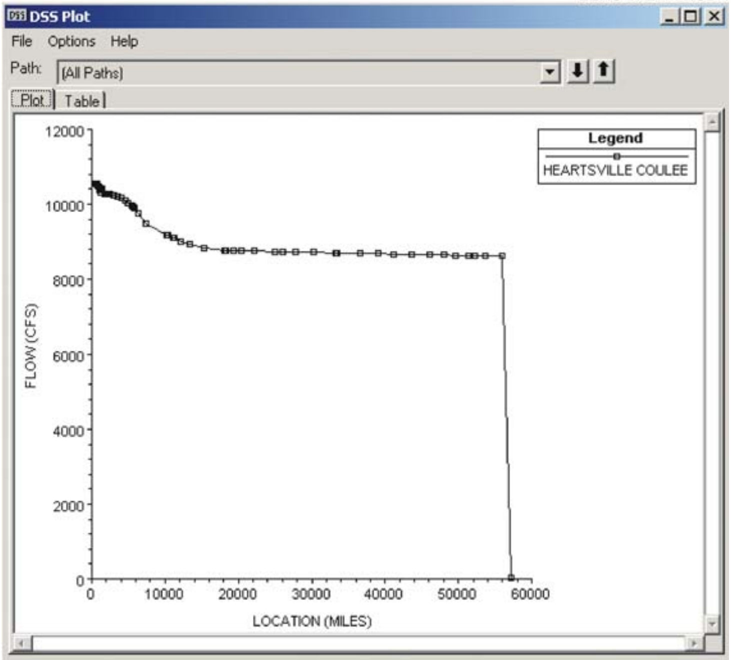


River: RRN
Reach: Downstream
River Sta.: 164 Obs WS Q
☑ Plot Stage ☑ Plot Flow ☑ Obs Stage ☑ Obs Flow ☐ Use Ref Stage

Peak Stage = 832.27 (ft)
Time = 22Apr1997
Peak Flow = 102424.80
Time = 22Apr1997
Volume = 3651294.5

Figure C-43. Plot showing the observed and predicted discharges and water surface elevations at Grand Forks. It should be noted that this station was not used for model calibration. The results are shown for informational purposes only. The observed stages were obtained from USACE.

EERC BK29706.CDR



Path: (All Paths)

Figure C-44. Plot showing the predicted maximum discharge profile along the Heartsville Coulee in 1997. The location is measured from the point where the overflow occurred in the vicinity of Thompson Bridge located on the Red River of the North would flow into the coulee.

APPLICATION CONSIDERATIONS

To appropriately apply ACE-M and EERC-M, the following aspects should be considered:

- The models included the major tributaries and overflows that occurred in 1997.
- The models were sufficiently calibrated in accordance with the 1997 flood; however, both should be validated using other historical floods.
- The HEC–RAS models used flows simulated by the SWAT models which are capable of predicting flows from ungauged areas. This minimizes uncertainty and/or inaccuracy caused by trying to calculate flows from ungauged areas.
- The models did not consider ice jamming because no data were available for describing this specific hydraulic phenomenon.
- The geometric data included in the models represent current ground-truth conditions. In particular, the current topography and geomorphology in the Grand Forks–East Grand Forks city limits subreach have been dramatically changed from these in 1997.
- The models were set up to only simulate the spring flood. ACE-M has a simulation time window from March 25 to May 25, and EERC-M has a time window from April 10 to May 10. An earlier start date might leave more days for the models to converge; however, EERC researchers felt this would not affect the evaluation of Waffle storage and its impacts on the Red River. For other modeling purposes, the model may need to encompass an earlier start date. This may require special tactics, such as implementation of pilot channels, to simulate the frozen conditions of the northern tributaries, which tend to make the models divergent.
- As additional observed flow data become available, these can be used to substitute the corresponding SWAT-simulated values which were used in these models. Also, observed and SWAT-simulated flows can be conjunctively used to conduct various scenarios or “what-if” analyses.

MODELED FLOOD CREST REDUCTIONS ALONG THE MAIN STEM

Reductions at Control Locations

Along the main stem, nine locations, namely, Wahpeton, Hickson, Fargo, Halstad, Grand Forks, Oslo, Drayton, Pembina, and Emerson, were selected to examine the effects of Waffle storage on reducing a 1997-type flood. These locations correspond to the USGS gauging station locations (Figures C-33 and C-34). The observed daily stream flows were obtained from USGS and Manitoba Water Stewardship, whereas the observed water surface elevations were obtained from USACE.

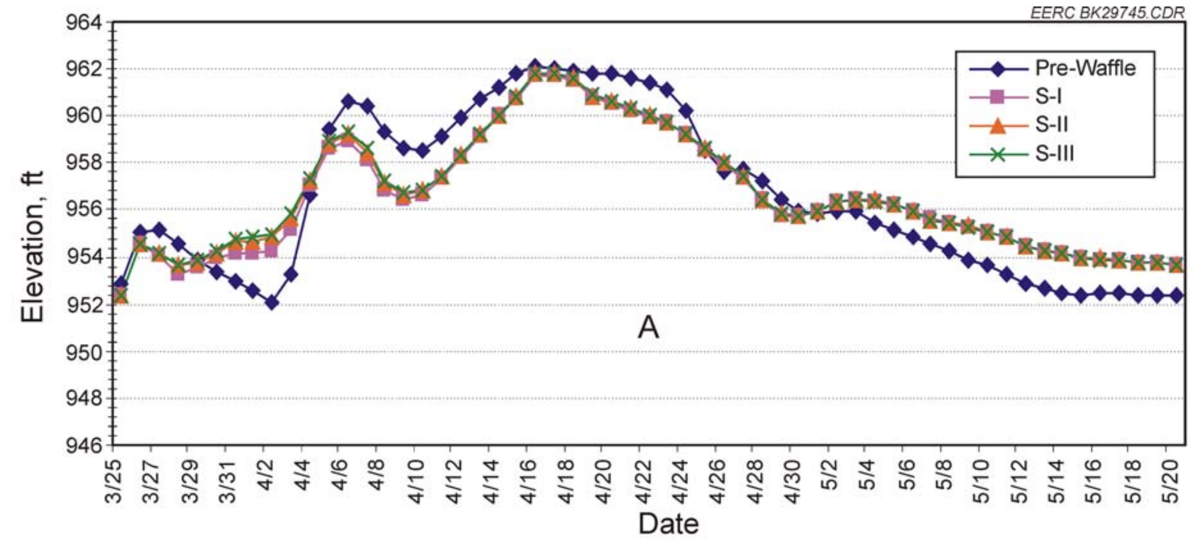
As a result of S-I, the 1997 flood crests would be lowered by 1.0 to 5.42 ft along the reach upstream of Pembina and by 0.85 ft at Emerson (Table C-28). The crest at Wahpeton would be lowered by 5.42 ft, and the crests at Fargo and Grand Forks would be reduced by 3.46 and 1.89 ft, respectively. Compared with that for S-I, the flood crests for S-II and S-III were predicted to be only 0.06 to 0.45 ft higher. This indicates that even 50% of the ultraconservative Waffle storage estimates would still have a measurable effect on reducing the flood crests along the Red River main stem. S-III would reduce the flood crests at Wahpeton, Fargo, and Grand Forks by 5.12, 1.26, and 1.56 ft, respectively. At Emerson, the flood crest would be lowered by 0.72 ft. The predicted flow and water surface elevation hydrographs for the pre-Waffle condition S-I, S-II, and S-III at the nine locations are shown in Figures C-45 to C-51.

To further investigate potential Waffle storage effects, two additional storage combinations were formulated and analyzed for each of the three scenarios. Combination I assumes that Waffle storage would only be implemented in the watersheds upstream of Halstad, and not downstream. In contrast, Combination II considers Waffle storage only in the watersheds

Table C-28. Predicted Reductions of the 1997 Flood Crests Along the Red River of the North Main Stem

				Maximum Water Surface Elevation, ft		
Station	Cross Section No.	Datum, ft	Pre-Waffle	Scenario I (S-I)	Scenario II (S-II)	Scenario III (S-III)
Wahpeton (USGS 05051500)	XS 548.595	942.97	962.07	961.79	961.84	961.84
Hickson (USGS 05051522)	XS 485.041	877.06	914.70	909.28	909.44	909.58
Fargo (USGS 05054000)	XS 452.92	861.80	901.36	897.90	898.06	898.18
Halstad (USGS 05064500)	XS 375.247	826.65	867.31	865.93	866.00	866.05
Grand Forks (USGS 05082500)	XS 163	779.00	831.99	830.10	830.25	830.43
				[830.70]*	[830.76]	[830.81]
				(831.51)	(831.54)	(831.67)
Oslo (USGS 05083500)	XS 107	772.65	810.95	809.92	810.45	810.53
				[810.25]	[810.65]	[810.67]
				(810.17)	(810.59)	(810.64)
Drayton (USGS 05092000)	XS 68	755.00	800.54	799.53	799.87	799.98
				[800.18]	[800.21]	[800.24]
				(800.10)	(800.15)	(800.21)
Pembina (USGS 05102490)	XS 16	739.45	794.39	793.29	793.35	793.44
				[793.97]	[793.99]	[794.01]
				(793.82)	(793.85)	(793.92)
Emerson (USGS 05102500)	XS 1	700.00	792.32	791.47	791.53	791.60
				[792.03]	[792.05]	[792.07]
				(791.91)	(791.94)	(791.99)

* The numbers in [ ] are for the combinations that the corresponding scenarios would be adopted for the watersheds upstream of Halstad but would not be adopted for the downstream watersheds. On the other hand, the numbers in ( ) are for the combinations that the corresponding scenarios would not be adopted for the watersheds upstream of Halstad but would be adopted for the downstream watersheds.



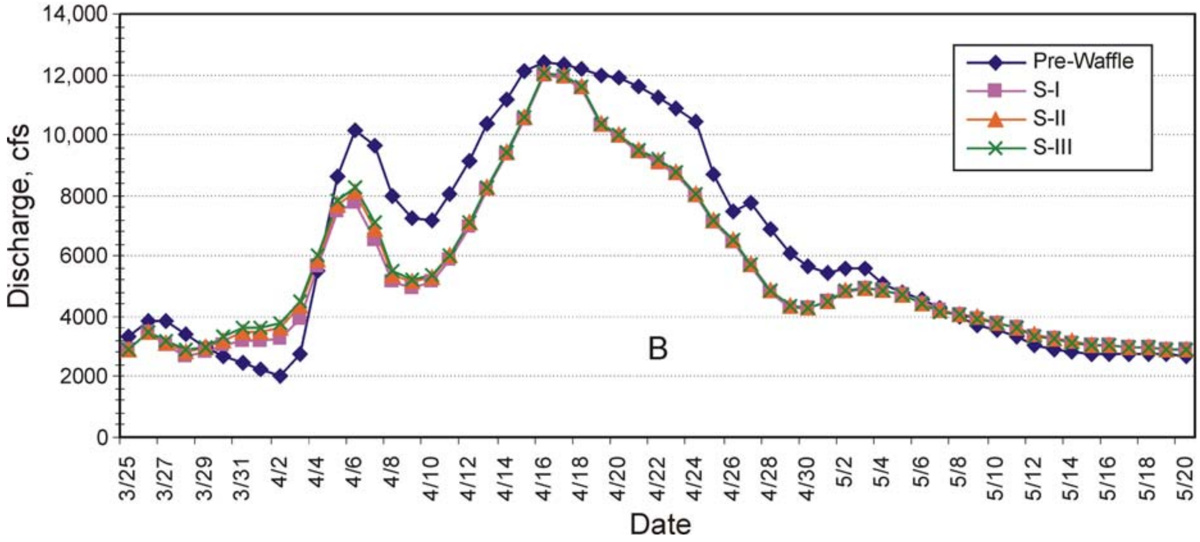


Figure C-45. Predicted reductions of the 1997 flood (A) crest and (B) discharge at Wahpeton.

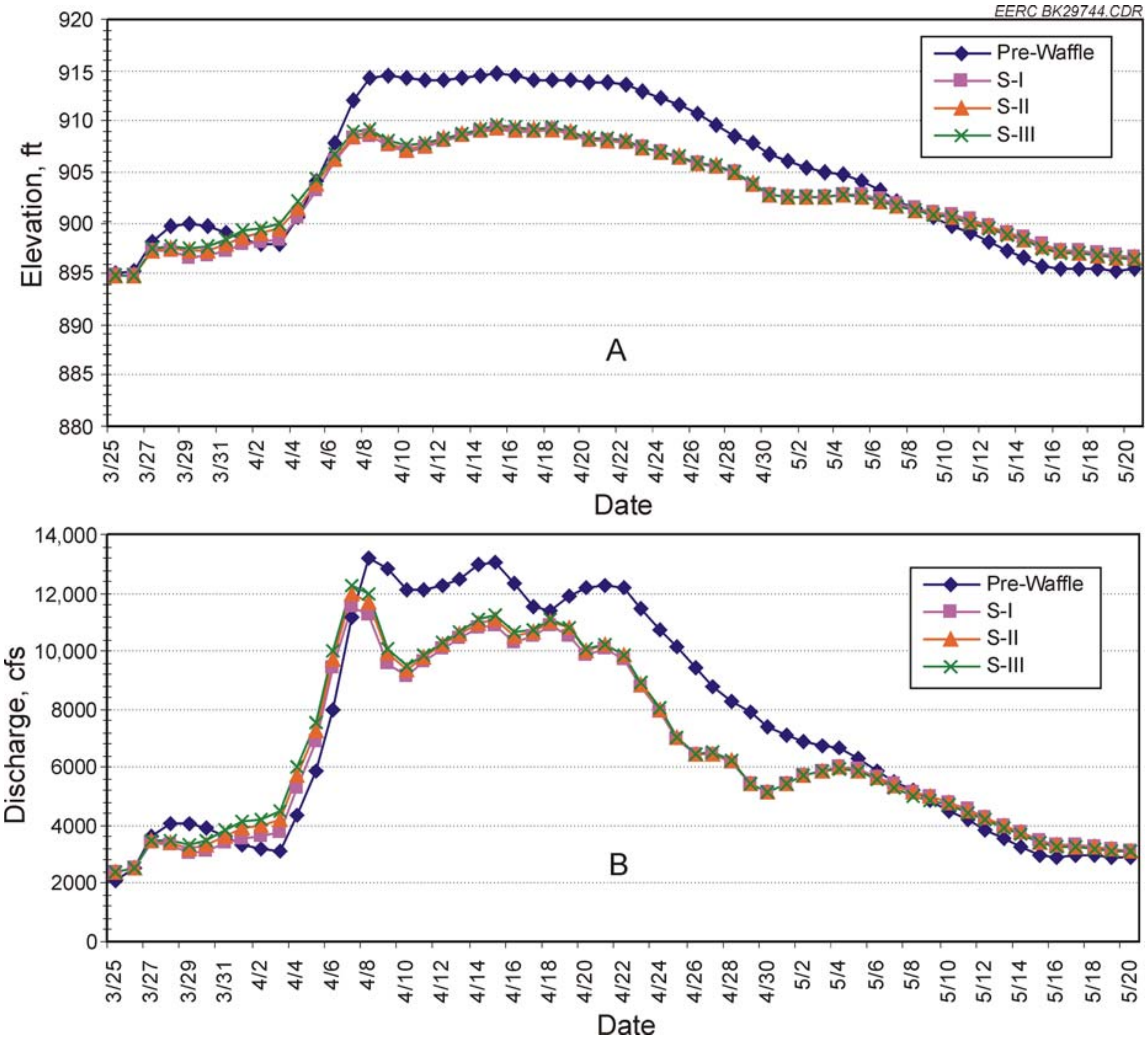


Figure C-46. Predicted reductions of the 1997 flood (a) crest and (b) discharge at Hickson.

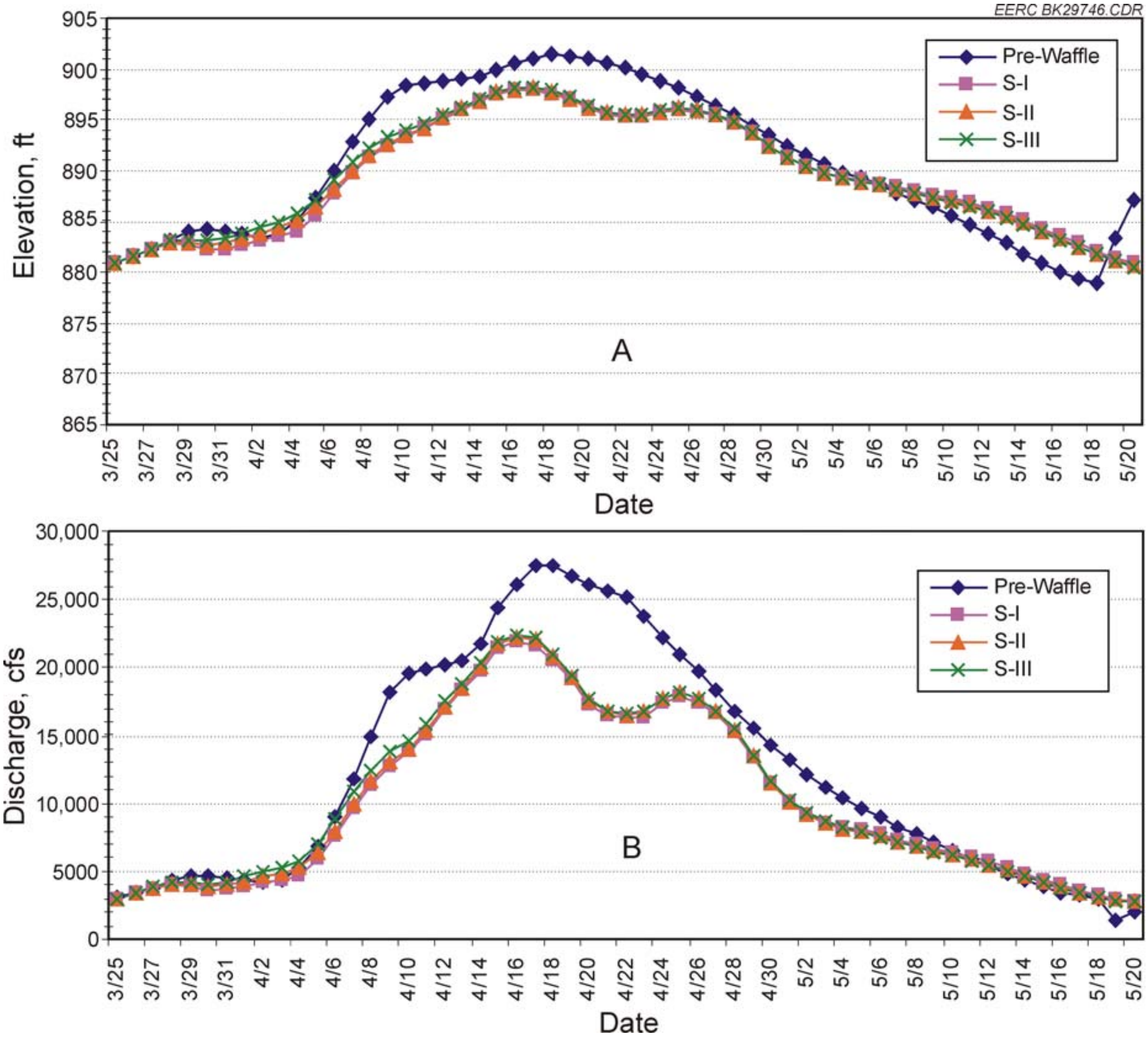


Figure C-47. Predicted reductions of the 1997 flood (A) crest and (B) discharge at Fargo.

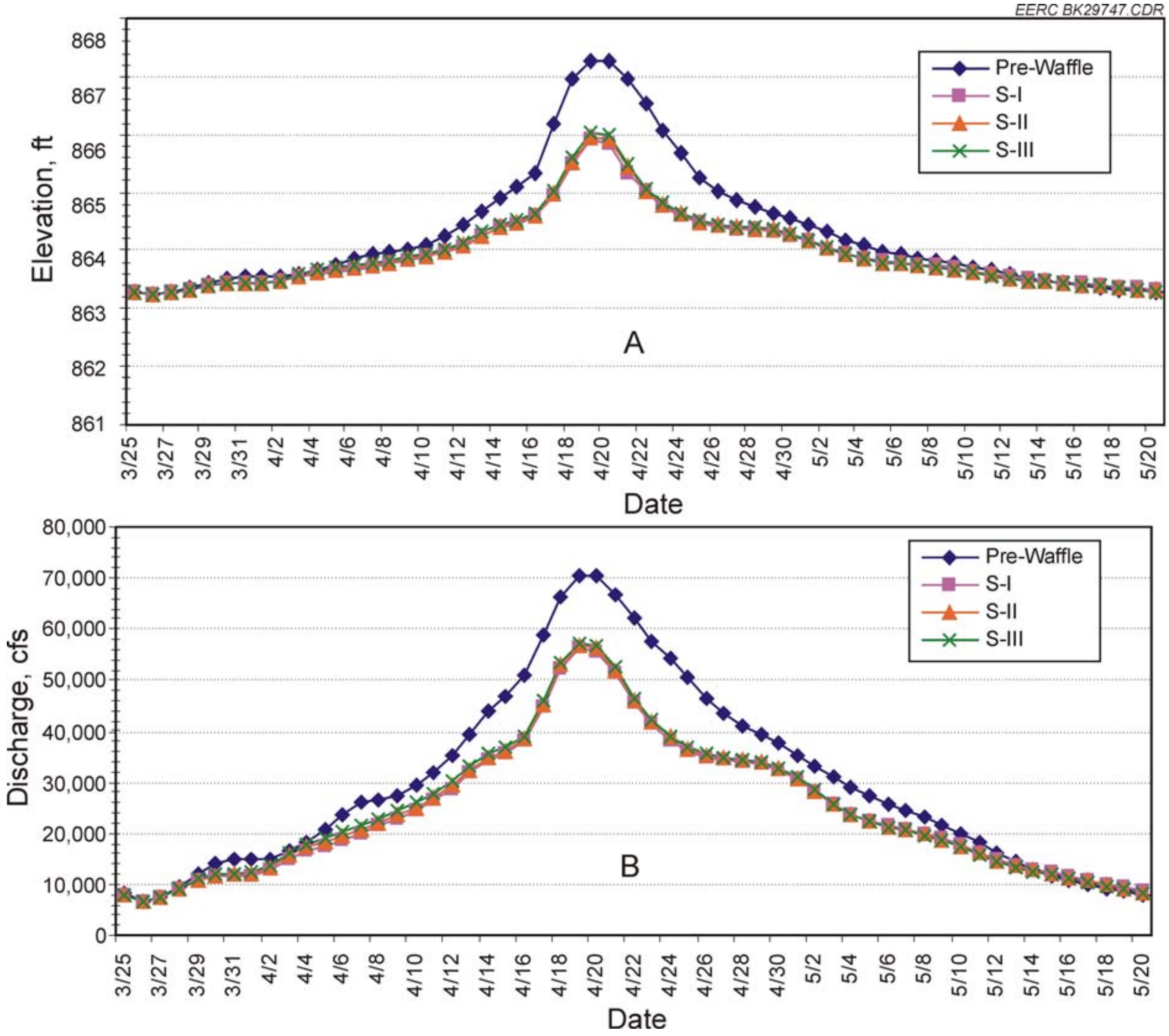


Figure C-48. Predicted reductions of the 1997 flood (A) crest and (B) discharge at Halstad.

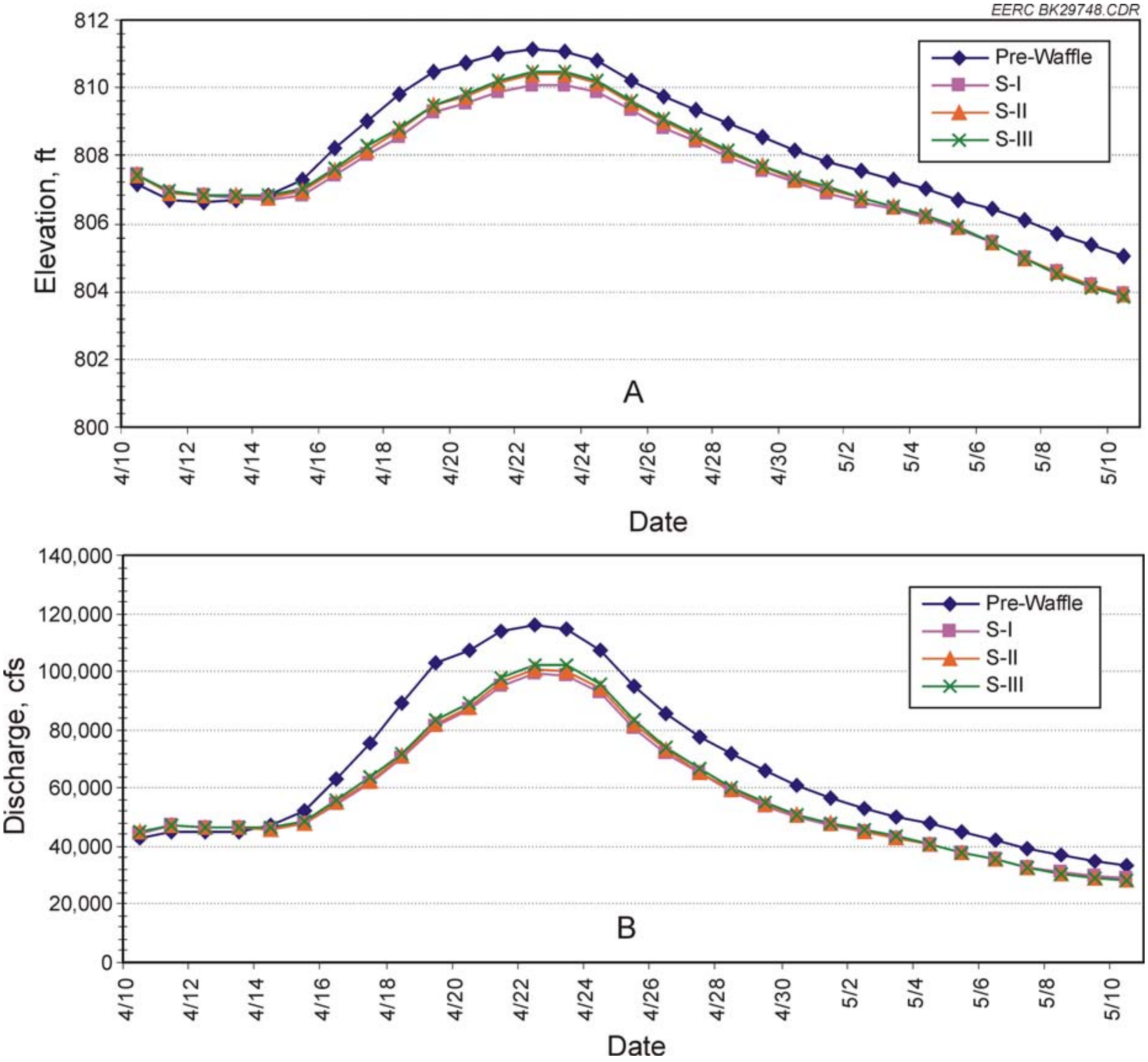


Figure C-49. Predicted reductions of the 1997 flood (A) crest and (B) discharge at Grand Forks.

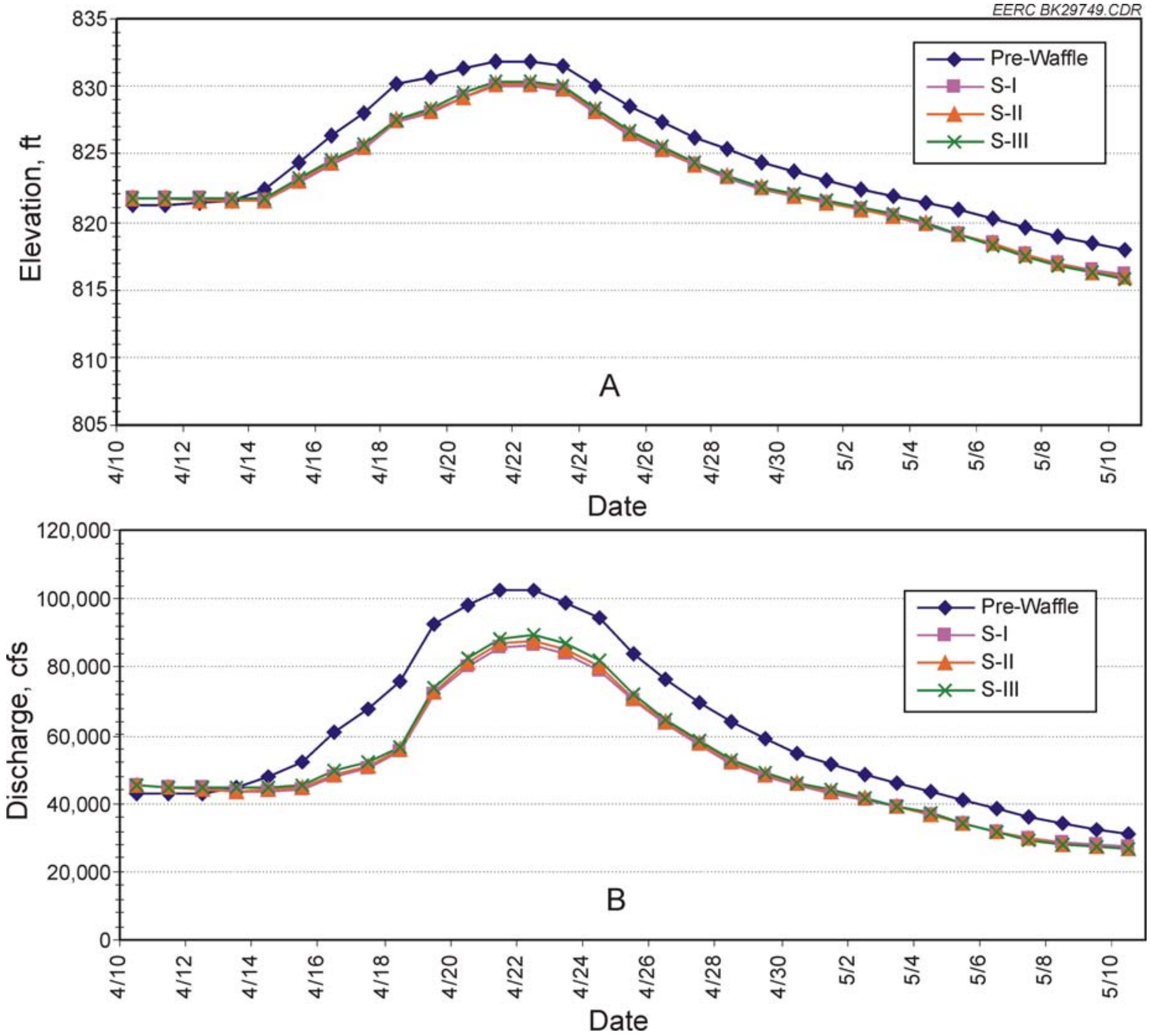


Figure C-50. Predicted reductions of the 1997 flood (A) crest and (B) discharge at Oslo.

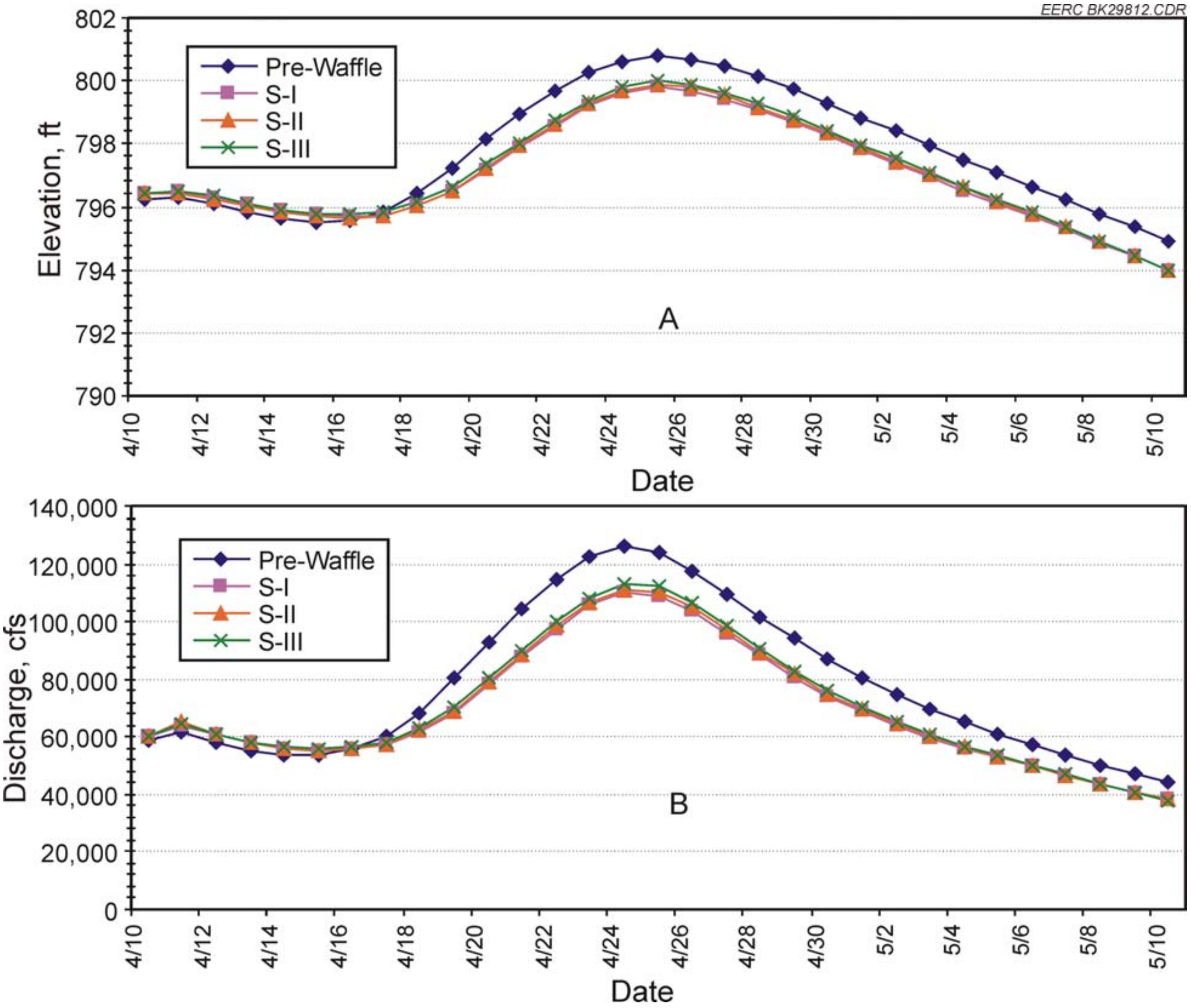


Figure C-51. Predicted reductions of the 1997 flood (A) crest and (B) discharge at Drayton.

downstream of Halstad. For example, the assumption for Scenario S-I, Combination I, is that the watersheds upstream of Halstad store 100% of the identified Waffle storage, whereas the watersheds downstream of Halstad contain zero Waffle storage.

In Table C-28, brackets present the results for Combination I and parentheses for Combination II. Overall, the predicted flood crests for Combination I were higher than the corresponding values for Combination II, implying that Waffle storage in the watersheds downstream of Halstad would contribute to flood crest reductions along the reach from Halstad to Emerson. However, a close examination indicated that the contributions would only be as high as 0.15 ft for S-I and 0.09 ft for S-III. In contrast, Waffle storage in the watersheds upstream of Halstad would be more important for reducing flood crests along the entire Red River main stem.

Water Surface Profiles

Figures C-52 and C-53 show the water surface profiles for a 1997-type flood along the Red River main stem reaches from Emerson to Halstad and from Halstad to White Rock Dam, respectively. In Figure C-52, the profiles for the pre-Waffle condition, S-I, and Combination II are drawn, and in Figure C-53, the profiles for the pre-Waffle condition, S-I, S-II, and S-III are plotted. The profiles indicate that the Waffle would have more effect on reducing the flood crests along the main stem from just downstream of Grand Forks to Halstad and from approximately 18 mi downstream of Fargo to about 5 mi upstream of the Richard County Road 28 near Abercrombie. In addition, the contribution of Waffle storage in the watersheds downstream of Halstad to flood crest reductions from Emerson to Halstad would be minor compared with the

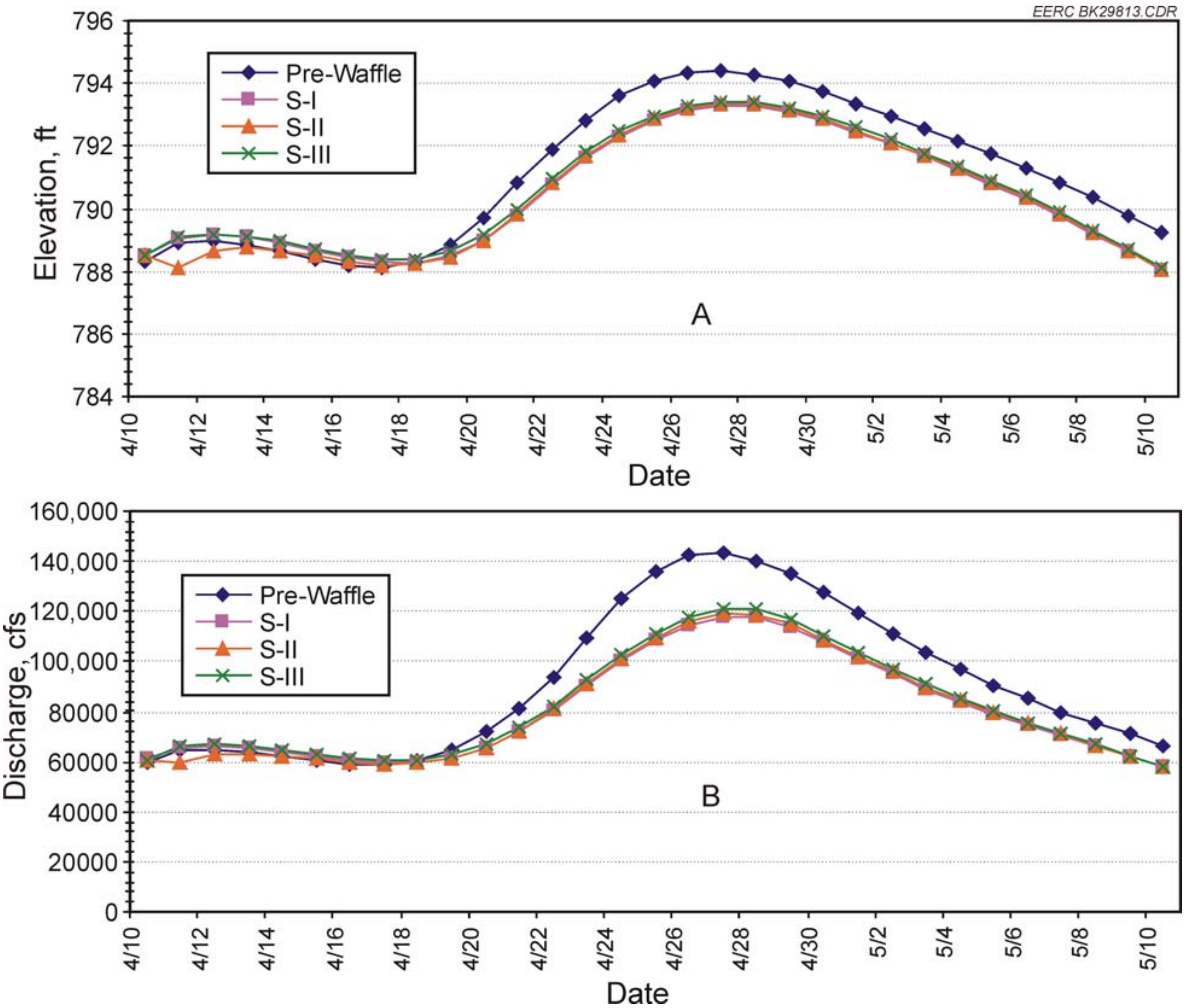


Figure C-52. Predicted reductions of the 1997 flood (A) crest and (B) discharge at Pembina.

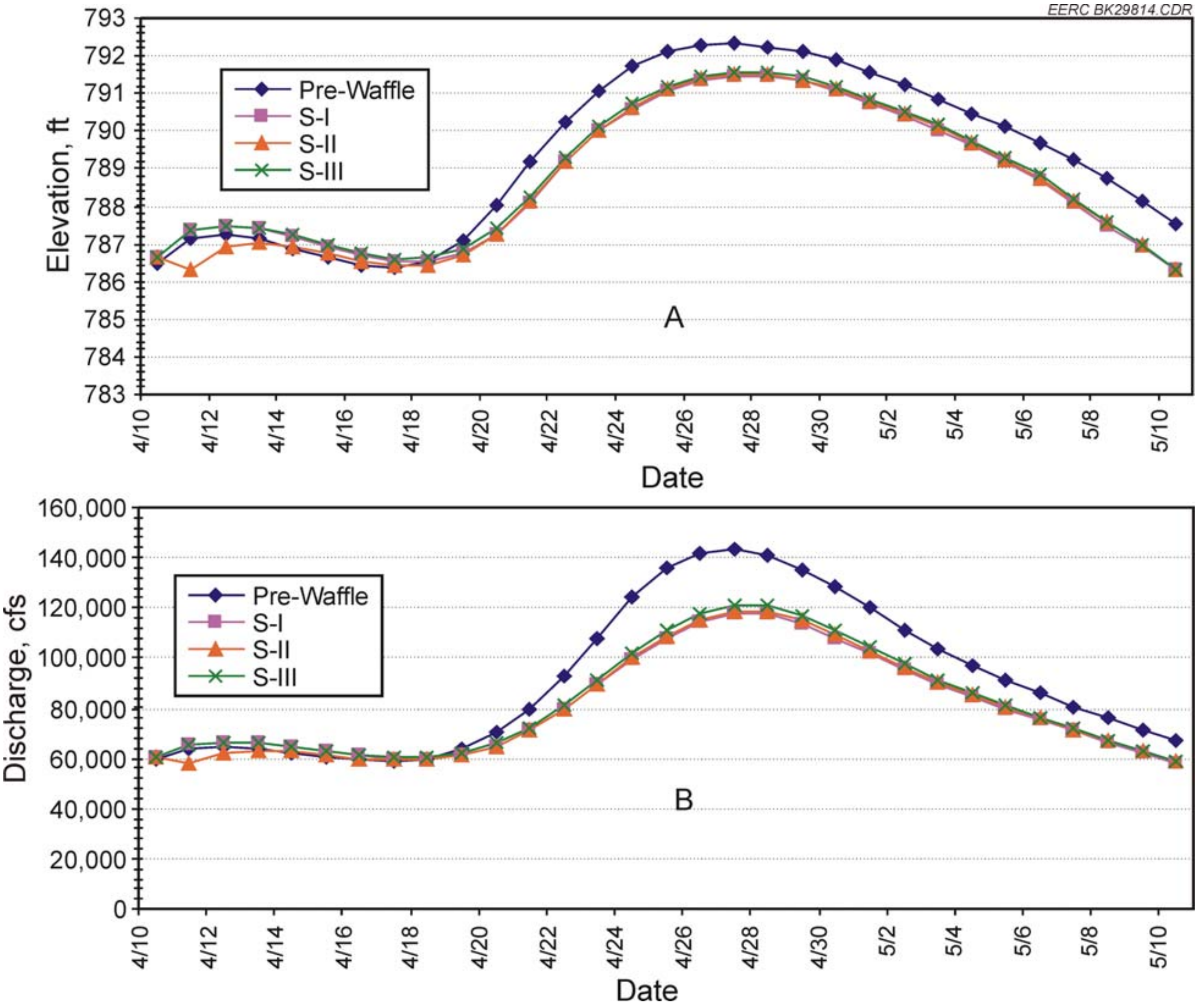


Figure C-53. Predicted reductions of the 1997 flood (A) crest and (B) discharge at Emerson.

effects of Waffle storage in the upstream watersheds. Further, because of the small scale, the predicted differences among the three scenarios (i.e., S-I, S-II, and S-III) are hardly differentiable in Figure C-54. For this reason, Figure C-55 does not show the predicted profiles for S-II and S-III. The differences at nine control points, which correspond to USGS gauging stations located within the limits of major towns and cities along the main stem, are shown in Table C-28.

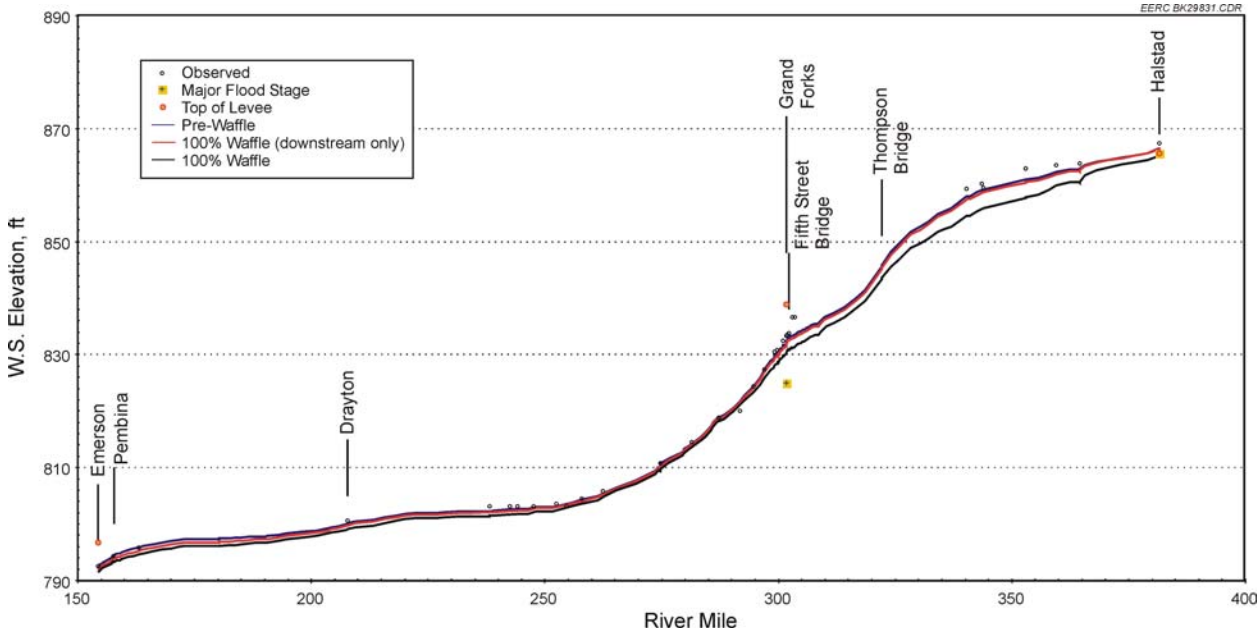


Figure C-54. Predicted water surface elevations along the main stem reach from Emerson to Halstad for the 1997-type flood. Combination II is that the watersheds upstream of Halstad would use zero storage but the downstream watersheds would adopt Scenario I (S-I), which corresponds to the 100% identified Waffle storages.

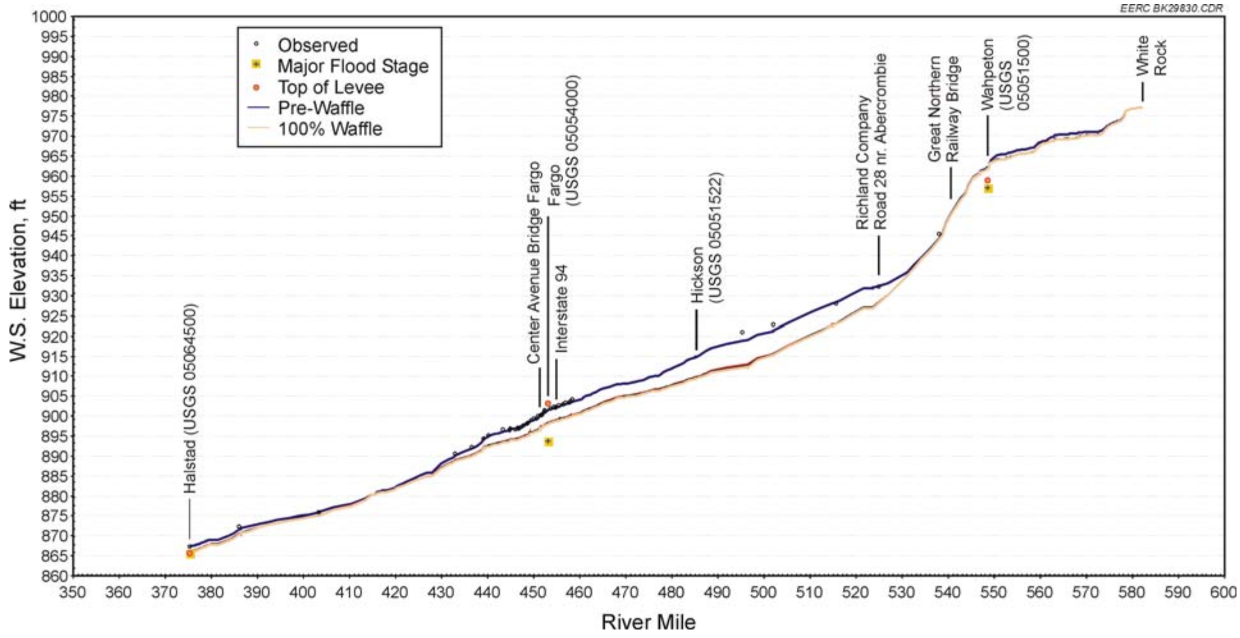


Figure C-55. Predicted water surface elevations along the main stem reach from Halstad to just downstream of White Rock Dam for the 1997-type flood.

CONCLUSIONS AND RECOMMENDATIONS

This study evaluated the effects of the Waffle on flood reduction in the Red River of the North Basin using coupled SWAT and HEC–RAS hydrodynamic models. The SWAT models were set up for 31 modeling domains, of which 17 are located in Minnesota and the other 14 in North Dakota. A modeling domain was defined in terms of the USGS 8-digit HUCs; however, watersheds that spanned both states were redelineated into two components: one for the North Dakota side of the watershed and one for the Minnesota side of the watershed. The available data on observed daily stream flows for the 1997 flood were used to calibrate the SWAT models. When the data were unavailable, the models were verified based on scientific judgment and/or peak discharge values obtained from various sources (e.g., consulting companies). In addition, the Minnesota SWAT models and one North Dakota model were validated using the other historical floods that occurred in 1979, 1978, 1975, 1969, and 1966. Statistical parameters used to determine the calibration and/or validation results indicated that the SWAT models are accurate enough for evaluating the effects of the Waffle. Further, ACE-M, the HEC–RAS model for the main stem reach from White Rock Dam to Halstad, and EERC-M, the HEC–RAS model for the reach from Halstad to Emerson, were calibrated in accordance with the 1997 flood.

The evaluation indicated that the Waffle would reduce flooding within the watersheds as well as along the main stem. For some watersheds, the Waffle would reduce the 1997 peak discharges by as high as 59.2%, whereas the percentage reductions for some of the other watersheds would be low. The reduction effects are a function of the ratio of Waffle storage volumes to watershed area, the spatial distribution of the Waffle storage locations, the shape of the watershed, and the characteristics of individual floods (i.e., magnitude and hydrograph shape).

Modeling indicates that the Waffle would lower the 1997 flood crests by 1.0 to 5.42 ft along the main stem reach upstream of Pembina and by 0.85 ft at Emerson. The Waffle would have more effects on reducing main stem flood crests from just downstream of Grand Forks to Halstad and from approximately 18 mi downstream of Fargo to about 5 mi upstream of the Richard County Road 28 near Abercrombie. In addition, Waffle storage in the watersheds upstream of Halstad would be more important for reducing the flood crests along the entire main stem than those of the downstream watersheds.

Herein, we make the following recommendations for future research efforts:

- The North Dakota SWAT models should be validated using other historical flood events.
- The HEC–RAS models should be validated using other historical flood events. In addition, an earlier start date (e.g., March 10) may need to be used.
- An interface should be developed to automate the data transfer from the SWAT models to the HEC–RAS models.

- More Waffle scenarios (e.g., 25% of the identified storage) and combinations should be analyzed to identify a set of optimal or cost-effective options that would use the fewest possible sections but still achieve the required flood reductions.

- The models should be expanded and enhanced for other studies, such as water quality and best management practices.

REFERENCES

Bengtson, M.L., and Padmanabhan, G., 1999, Hydrologic model for assessing the influence of wetlands on flood hydrographs in the Red River Basin—development and application: Fargo, North Dakota, North Dakota State University North Dakota Water Resources Research Institute, 1999.

Bluemle, J.P., 1997, Factors affecting flooding in the Red River Valley: Proceedings of the North Dakota Academy of Science, v. 51, no. 1, p. 17–20.

De Laney, T.A., 1955, Benefits to downstream flood attenuation and water quality as a result of constructed wetlands in agricultural landscapes: Journal of Soil and Water Conservation, v. 50, no. 6, p. 620–626.

Federal Emergency Management Agency, 1987, Flood insurance study: City of Grand Forks, North Dakota.

Federal Emergency Management Agency, 1995a, Flood insurance study—guidelines and specifications for study contractors.

Federal Emergency Management Agency, 1995b, Flood insurance study, City of Fargo, North Dakota.

Federal Emergency Management Agency, 2000, National Flood Insurance Program regulations.

Fread D.L., and Lewis, J.M., 1998, NWS FLDWAV model: Silver Spring, Maryland, Hydrologic Research Laboratory, Office of Hydrology, National Weather Service, National Oceanic and Atmospheric Administration, 1998.

Halliday, R., and Jutila, S., 2000, Hydrologic and hydraulic modeling in the Red River Basin—a report of the Tools Group: The International Red River Basin Task Force, International Joint Commission.

Houston Engineering Inc., 1999, Hydrologic routing of the 1997 Red River flood: Study report for the Red River Watershed Management Board.

International Joint Commission, 1997, Red River flooding—short-term measures: Interim report of the International Red River Basin Task Force to the International Joint Commission, Ottawa – Washington, 1997, 65 p.

Napier, T.L., McCarter, S.E., and McCarter, J.R., 1995, Willingness of Ohio land owner–operators to participate in a wetlands trading system: Journal of Soil and Water Conservation**,** v. 50, no. 6, p. 648–656.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., and King, K.W., 2002a, Soil and Water Assessment Tool—theoretical documentation (Version 2000): Temple, Texas, Grassland, Soil and Water Research Laboratory of Agricultural Research Service, and Blackland Research Center of Texas Agricultural Experiment Station.

Sellars, C.D., 1999a, Probable maximum floods—making a collective judgment: Unpublished paper.

Sellars, C.D., Buschiazzo, E., and Garrett, M., 1999b, Hydrodynamic modeling as a planning tool, in Proceedings of the Canadian Water Resources Association Conference: Red River flooding – decreasing our risks: Winnipeg, MB, 1999.

Sellars, C.D., Buschiazzo, E., Garrett, M., and Farlinger, D., 1999c, Hydrodynamic modeling of the 1997 Red River flood, in Proceedings of the Canadian Water Resources Association Conference—confronting uncertainty – managing change in water resources and the environment; 1999.

Shultz, S.D., 2000, Wetland storage to reduce flood damages in the Red River, in Land stewardship of the 21st century, U.S. Department of Agriculture Forest Service Proceedings: Rocky Mountain Research Station, 2000, p. 363–366.

Shultz, S.D., 1999, The feasibility of wetland restoration to reduce flooding in the Red River Valley—a case study of the Maple (ND) and Wild Rice (MN) Watersheds: Agricultural Economics Report 432, Fargo, North Dakota, Department of Agricultural Economics, Agricultural Experiment Station, North Dakota State University, 1999.

Shutov, V.A., 2000, Snow cover in various relief and landscape conditions, in Water resources in extreme environments: American Water Resources Association, 2000, p. 19–24.

Socolofsky, S., Adams, E.E., and Entekhabi, D., 2001, Disaggration of daily rainfall for continuous watershed modeling: Journal of Hydrological Engineering, v. 6, no. 4, p. 300–309.

Stoner, J.D., Lorenz, D.L., Wiche, G.J., and Goldstein, R.M., 1993, Red River of the North Basin, Minnesota, North Dakota, and South Dakota: Water Resources Bulletin, v**.** 29, no. 4, p. 575–615.

Thomas, W.O., Lumb, A.M., Flynn, K.M., and Kirby, W.H., 1998, User's manual for program PEAKFQ, annual flood frequency analysis using Bulletin 17B guidelines: 89 p.

U.S. Army Corps of Engineers, 2001, Hydrologic analyses—the Red River of the North main stem Wahpeton–Breckenridge to Emerson, Manitoba: St. Paul, Minnesota: U.S. Army Corps of Engineers final hydrology report.

U.S. Army Corps of Engineers Hydrologic Engineering Center, 1992a, HEC–2 water surface profiles user's manual.

U.S. Army Corps of Engineers Hydrologic Engineering Center, 1992b, Flood flow frequency analysis user's manual (HEC–FFA).

U.S. Army Corps of Engineers Hydrologic Engineering Center, 1998a, HEC–1 flood hydrograph package user's manual.

U.S. Army Corps of Engineers Hydrologic Engineering Center, 2001a, HEC–RAS river analysis system user's manual.

U.S. Army Corps of Engineers Hydrologic Engineering Center, 2001b, Hydrologic modeling system HEC–HMS user's manual.

U.S. Army Corps of Engineers, 1960, Runoff from Snowmelt: EM1110-2-1406.

U.S. Army Corps of Engineers, 1985, Feasibility report—supporting documentation, Red River of the North, Walsh and Pembina Counties, North Dakota farmstead flood protection.

U.S. Army Corps of Engineers, 1998b, General reevaluation report and environmental impact statement – East Grand Forks, Minnesota, and Grand Forks, North Dakota—local flood reduction project, Red River of the North.

U.S. Army Corps of Engineers, 2001c, Hydrologic analyses, the Red River of the North main stem, Wahpeton/Breckenridge to Emerson, Manitoba: Final hydrology report.

U.S. Army Corps of Engineers and Federal Emergency Management Agency, 2003, Regional Red River flood assessment report: Wahpeton, North Dakota–Breckenridge, Minnesota, to Emerson, Manitoba: St. Paul, Minnesota, the U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers, 2005, Fargo–Moorhead upstream feasibility study Phase I: Hydrology and hydraulics analysis: Final report, St. Paul, Minnesota, the U.S. Army Corps of Engineers.

Warkentin, A.A., 1999, Red River at Winnipeg hydrometeorological parameter generated floods for design purposes, in Proceedings of the Canadian Water Resources Association Winnipeg Conference—Red River flooding – decreasing our risks: Winnipeg, MB, September 1999.

West Consultants Inc., 2002, Minnesota and Red River CWMS—watershed modeling: Final report, San Diego, California, West Consultants Inc., 2002.

World Meteorological Organization, 1973, Manual for estimation of probable maximum precipitation: Operational Hydrology Report 1.

Zien, T.R., 1997, UNET unsteady flow models for the Red River of the North: Proceedindgs of the North Dakota Academy of Science, v. 51, no. 1, p. 21–25.

APPENDIX D

SOIL CHEMISTRY DATA

Shelly 2004 – Low-Ground Averages

Parameter	Units	Fall 2003 Av	Spring 2004 Av	Standard Deviation	Standard Deviation, %
Boron	ppm	1.5	1.7	0.2	10.6
Calcium	ppm	5377	5182	483	29.9
Cation Exchange Capacity	meq	39.6	38.2	5.4	12.7
Chloride	lb/acre	34	20	8.3	55.0
Copper	ppm	1.43	1.44	0.11	7.4
Iron	ppm	18.9	14.8	1.8	9.9
Magnesium	ppm	1414	1368	226	14.0
Nitrate-N					
0–6 inches	lb/acre	57	41	5.3	41.5
6–24 inches	lb/acre	42	38	6.2	46.0
24–42 inches	lb/acre	23	30	3	40.0
Organic Matter	%	3.7	3.2	0.6	11.3
Phosphorus	ppm	8	8	1.3	12.2
Potassium	ppm	284	258	75.9	20.8
Sodium	ppm	44	55	3	8.4
Soluble Salts	mS/cm	0.80	0.75	0.07	10.4
Sulfate-S	lb/acre	102	107	7	13.7
Zinc	ppm	0.63	0.51	0.03	4.0

Shelly 2004 – High-Ground Averages

Parameter	Units	Fall 2003 Av	Spring 2004 Av	Standard Deviation	Standard Deviation, %
Boron	ppm	1.9	1.9	0.2	8.9
Calcium	ppm	5017	5062	214	3.8
Cation Exchange Capacity	meq	36.9	35.9	2.0	5.0
Chloride	lb/acre	48	40	7	35.9
Copper	ppm	0.98	1.20	0.06	6.6
Iron	ppm	13.8	12.8	2.7	21.2
Magnesium	ppm	1322	1171	134	10.7
Nitrate-N					
0–6 inches	lb/acre	17	25	1.6	9.1
6–24 inches	lb/acre	38	38	2.9	11.6
24–42 inches	lb/acre	15	21	1.7	10.5
Organic Matter	%	3.6	3.1	0.3	7.0
Phosphorus	ppm	6	7.5	0.8	16.3
Potassium	ppm	241	256	16	6.2
Sodium	ppm	35	36	8.8	34.1
Soluble Salts	mS/cm	0.55	0.47	0.02	3.3
Sulfate-S	lb/acre	53	49	31	57.5
Zinc	ppm	0.54	0.50	0.01	3.6

Shelly 2005 – Low-Ground Averages

Parameter	Units	Fall 2004 Av	Spring 2005 Av	Standard Deviation	Standard Deviation, %
Boron	ppm	1.6	1.3	0.2	10.6
Calcium	ppm	5443	5446	483	29.9
Cation Exchange Capacity	meq	41.8	43.0	5.4	12.7
Chloride	lb/acre	15.0	24.0	8.3	55.0
Copper	ppm	1.48	2.10	0.11	7.4
Iron	ppm	18.2	22.8	1.8	9.9
Magnesium	ppm	1614	1760	226	14.0
Nitrate-N					
0–6 inches	lb/acre	12.8	12.5	5.3	41.5
6–24 inches	lb/acre	13.5	13.5	6.2	46.0
24–42 inches	lb/acre	7.5	10.5	3	40.0
Organic Matter	%	5.2	3.4	0.6	11.3
Phosphorus	ppm	10.3	10.0	1.3	12.2
Potassium	ppm	366.0	351.5	75.9	20.8
Sodium	ppm	37	40	3	8.4
Soluble Salts	mS/cm	0.67	0.70	0.07	10.4
Sulfate-S	lb/acre	52	45	7	13.7
Zinc	ppm	0.75	0.70	0.03	4.0

Shelly 2005 – High-Ground Averages

Parameter	Units	Fall 2004 Av	Spring 2005 Av	Standard Deviation	Standard Deviation, %
Boron	ppm	1.9	1.8	0.2	8.9
Calcium	ppm	5626	5193	214	3.8
Cation Exchange Capacity	meq	39.3	37.2	2.0	5.0
Chloride	lb/acre	19	28	7	35.9
Copper	ppm	0.96	1.20	0.06	6.6
Iron	ppm	12.8	11.3	2.7	21.2
Magnesium	ppm	1254	1274	134	10.7
Nitrate-N					
0–6 inches	lb/acre	18	16	1.6	9.1
6–24 inches	lb/acre	25	26	2.9	11.6
24–42 inches	lb/acre	17	35	1.7	10.5
Organic Matter	%	4.4	3.1	0.3	7.0
Phosphorus	ppm	5.0	4.0	0.8	16.3
Potassium	ppm	254	194	16	6.2
Sodium	ppm	26.0	23.5	8.8	34.1
Soluble Salts	mS/cm	0.56	0.49	0.02	3.3
Sulfate-S	lb/acre	54	23	31	57.5
Zinc	ppm	0.52	0.60	0.01	3.6

Gilby 2005 – Low-Ground Averages

Parameter	Units	Fall 2004 Av	Spring 2005 Av	Standard Deviation	Standard Deviation, %
Boron	ppm	2.6	0.5	0.4	26.9
Calcium	ppm	6064	3190	838	13.8
Cation Exchange Capacity	meq	44.9	26.8	6.3	13.9
Chloride	lb/acre	9501	252	4929	51.9
Copper	ppm	2.01	1.83	0.36	17.9
Iron	ppm	33.0	22.1	8.8	26.5
Magnesium	ppm	1521	1178	412	27.1
Nitrate-N					
0–6 inches	lb/acre	6.2	6.0	2.8	44.8
6–24 inches	lb/acre	7.0	NA	2.5	34.9
24–42 inches	lb/acre	4.0	NA	1.5	38.5
Organic Matter	%	12.4	2.0	2.9	23.5
Phosphorus	ppm	15.5	1.0	4.2	27.3
Potassium	ppm	232.7	179	33.2	14.3
Sodium	ppm	304	133	96	31.6
Soluble Salts	mS/cm	2.67	0.97	0.80	29.8
Sulfate-S	lb/acre	120	NA	NA	NA
Zinc	ppm	1.99	0.29	0.36	18.1

Gilby 2005 – High-Ground Averages

Parameter	Units	Fall 2004 Av	Spring 2005 Av	Standard Deviation	Standard Deviation, %
Boron	ppm	2.6	3.0	0.5	24.4
Calcium	ppm	7907	7063	1385	22.1
Cation Exchange Capacity	meq	48.2	46.2	6.1	16.1
Chloride	lb/acre	2165	1900	1451	73.0
Copper	ppm	1.20	1.71	0.12	13.7
Iron	ppm	11.9	19.8	1.8	18.7
Magnesium	ppm	895	1160	158	22.3
Nitrate-N					
0–6 inches	lb/acre	11.3	11.0	1.5	17.1
6–24 inches	lb/acre	6.0	18.0	3.0	56.6
24–42 inches	lb/acre	3.0	9.0	0.0	0.0
Organic Matter	%	8.5	6.0	1.9	27.5
Phosphorus	ppm	7.3	5.0	1.2	19.8
Potassium	ppm	319	252	18.7	7.7
Sodium	ppm	96.3	138.0	37.2	45.6
Soluble Salts	mS/cm	1.35	1.35	.32	29.2
Sulfate-S	lb/acre	120	120	NA	NA
Zinc	ppm	1.17	1.02	0.19	20.4

APPENDIX E

OUTREACH ACTIVITIES

Agency Meetings

Date (2007)	**Meeting Attendance/Presentations**	**Location**
1/19	Stephen/Argyle Central HS Video Interview	Grand Forks, ND
1/22 – 1/25	Red River Basin Commission (RRBC) Conference	Fargo, ND
3/–13 – 3/15	Third International Water Conference	Grand Forks, ND
3/29	Flood Damage Reduction Work Group Meeting	Crookston, MN
4-20	1997 Flood Symposium	Grand Forks, ND
4-25	CBC Radio Interview	Grand Forks, ND
Date (2006)	**Meetings Attendance/Presentations**	**Location**
1/11–1/13	Red River Basin Commission Conference	Winnipeg, MB
2/1	Cavalier County Soil Conservation District (SCD) Meeting	Langdon, ND
2/3	RRB Monitoring Advisory Committee Meeting	Fertile, MN
2/24	Water Quality Monitoring Advisory Committee Meeting	Grand Forks, ND
3/2	RRBC Meeting	Grand Forks, ND
3/14	RRBC Meeting	Forman, ND
3/20	Dakota Public Radio Interview	Grand Forks, ND
3/21	CBC Radio Interview	Grand Forks, ND
4/05–4/-6	Shallow Lakes Forum	Wilmar, MN
4/12	Minnesota Public Radio Interview	Grand Forks, ND
4/19	RRBC Water Management Workshop	Grand Forks, ND
4/27	Rotary Club Meeting	Crookston, MN
5/22	RRB Water Quality Team Meeting	Moorhead, MN
6/06	Two Rivers Watershed District (WD)	Hallock, MN
6/07	Flood Damage Reduction Work Group	Detroit Lakes, MN
6/14	Waffle Citizens' Advisory Board (CAB) Meeting	Grand Forks, ND
6/22	Waffle Agency Advisory Board (AAB) Meeting	Grand Forks, ND
6/26	RRB Water Quality Team Meeting	Moorhead, MN
7/25	Minnesota Pollution Control Agency Sediment Summit	Detroit Lakes, MN
7/28	Meeting with the Monitoring Advisory Committee	Fertile, MN
8/2–8/3	RRBC Meeting	Mahnomen, MN
8/9	Modeling Meeting	Grand Forks, ND
8/16	RRBC Planning Committee Meeting	Moorhead, MN
8/25	Water Quality Advisory Committee Meeting	Fertile, MN
10/26	Grand Forks County Farm Bureau	Grand Forks, ND
11/02	Waffle Economic Analysis discussion with North Dakota State University Researchers	Grand Forks, ND
11/02	RRB Commission Meeting	Grand Forks, ND
12/01	Total Maximum Daily Load (TMDL) Kickoff Meeting	Clearbrook, MN
12/05	EERC Capabilities discussion with Wild Rice WD	Grand Forks, ND
12/06	Modeling Meeting	Grand Forks, ND
12/13	Wild Rice WD	Ada, MN
Date (2005)	**Meeting Attendance/Presentations**	**Location**
1/11	Waffle AAB Meeting	Fargo, ND
1/11–1/14	22nd Annual RRB Land and Water International Summit Conference	Fargo, ND
2/3	Waffle CAB Meeting	Grand Forks, ND
2/8	U.S. Army Corps of Engineers, JOR Engineering, and the North Dakota State Water Commission discussion of Red River Modeling	Grand Forks, ND
2/17	Resource Conservation & Development (RC&D) Committee Meeting	Grafton, ND
3/5–3/9	Third Annual Conference on Watershed Management to Meet Water	Atlanta, GA

	Quality Standards and Emerging TMDL	
3/9	Red River High School Science Classes	Grand Forks, ND
3/15	Grand Forks Area Retired Teachers Group	Grand Forks ND
3/28	Alvarado Lion's Club	Alvarado, MN
3/31	Red River Water Management Board Meeting	Crookston, MN
4/6–4/7	RRB Institute Annual Conference	Winnipeg, MB
5/5	RRBC Meeting	Morris, Manitoba
5/12	KJ102 Radio Interview	Roseau, MN
5/16	UND Space Studies	Grand Forks, ND
5/17–5/19	Ecosystem Services Workshop	Washington, DC
5/24	East Grand Forks City Council Meeting	East Grand Forks, MN
6/6	Wahpeton City Council Meeting	Wahpeton ND
6/7	Digital Elevation Model (DEM) Scoping Meeting	Ada, MN
6/13	Grafton City Council Meeting	Grafton, ND
6/20	Hillsboro City Council Meeting	Hillsboro, ND
6/23	Waffle AAB Meeting	Grand Forks, ND
6/28	Waffle CAB Meeting	Grand Forks, ND
6/29	RRBC Modeling Committee	Moorhead, MN
6/29	Fargo–Moorhead Upstream Feasibility Study Phase I Results Meeting	Moorhead, MN
7/06	Ada City Council Meeting	Ada, MN
7/11	Aquatic Ecosystem Health Meeting	Grand Forks, ND
7/12	Warren City Council Meeting	Warren, MN
7/12–7/14	International Red River Board Meetings	Grand Forks, ND
7/18	West Fargo City Council Meeting	West Fargo, ND
7/29–8/3	Soil & Water Conservation Society Meeting	Rochester, NY
8/1	Lisbon City Council Meeting	Lisbon, ND
8/15	Breckenridge City Council Meeting	Breckenridge, MN
8/18	Bois De Sioux Watershed Meeting	Wheaton, MN
8/22	Buffalo/Red River Watershed Meeting	Barnesville, MN
8/25	Red Lake Watershed Meeting	Thief River Falls, MN
9/12–9/13	MN Flood Plain Managers’ Conference	Moorhead, MN
9/14	Wild Rice WD meeting	Ada, MN
9/19	Mayville City Council Meeting	Mayville, ND
9/21	Water Resource Board (WRB) Meeting	Grand Forks, ND
9/29–9/30	MIKE-11 Workshop	Moorhead, MN
10/03	Hallock City Council Meeting	Hallock, MN
10/04	Steele County WRB Meeting	Finley, ND
10/13	Cavalier County WRB Meeting	Langdon, MN
10/17	Traill County WRB Meeting	Hillsboro, ND
11/1	Two Rivers WD Meeting	Hallock, MN
11/7–11/11	American Water Resources Association Conference	Seattle, WA
11/21	Middle River/Snake River WD Meeting	Warren, MN
12/07	Waffle CAB Meeting	Grand Forks, ND
12/13–12/15	Soil and Water Assessment Tool (SWAT) Modeling Seminar	Grand Forks, ND
12/15	Waffle AAB Meeting	Grand Forks, ND
Date (2004)	**Meeting Attendance/Presentations**	**Location**
1/6	Polk County Farm Service Agency (FSA) Meeting	McIntosh, MN

1/12	Roseau Soil and Water Conservation District (SWCD) Meeting	Roseau, MN
1/14	Barnes County FSA Meeting	Valley City, ND
1/14	Waffle AAB Meeting	Moorhead, MN
1/14–1/16	RRBC Annual Conference	Moorhead, MN
1/18–1/20	North Dakota Grain Dealers Association Conference	Fargo, ND
1/20	Rough Riders Kiwanis Club Meeting	Fargo, ND
1/29	Aggassiz Club Meeting	Fargo, ND
2/9	Walhalla Chamber of Commerce	Walhalla, ND
2/10	Wetland Working Group Meeting	Fargo, ND
2/11	MIKE-11 Meeting	Moorhead, MN
2/12	Grand Forks Golden K (Kiwanis) Meeting	Grand Forks, ND
2/18–2/19	International Crop Expo	Grand Forks, ND
2/19	Barnes County FSA Meeting	Valley City, ND
2/24	Wilken County Township Boards Annual Meeting	Breckinridge, MN
3/05	Norman County Township Meeting	Ada, MN
3/09	West Polk County Township Annual Meeting	Crookston, MN
3/10	Wahpeton Kiwanis Club Meeting	Wahpeton, ND
3/11	Crookston Kiwanis Club Meeting	Crookston, MN
3/15	Clay County Township Officers Annual Meeting	Glyndon, MN
3/16	Clearwater County Commissioner Meeting	Bagley, MN
3/17	Grand Forks Kiwanis Meeting	Grand Forks, ND
3/18	Red Lake County Township Officers Meetings	Red Lake Falls, MN
3/18–19	Nature Conservancy Aquatic Partners & Expert Workshop	Grand Forks, ND
3/23	Hillsboro Kiwanis Meeting	Hillsboro, ND
3/24	CAB Meeting	Grand Forks, EERC
3/26	ND Science Teachers Association	Grand Forks, ND
3/27	Ransom County Township Meeting	Lisbon, ND
3/29	Grand Forks Kiwanis Club Meeting	Grand Forks, ND
3/29	Cavalier County Extension Meeting	Langdon, ND
4/1	Cass County Township Officers Association Meeting	Casselton, ND
4/5	Richland County Extension Meeting	Wahpeton, ND
4/6	Thief River Falls Kiwanis Meeting	Thief River Falls, MN
4/7	Soils Planning Conference	Fargo, ND
4/13	City Council/Mayor Meeting	Crookston, MN
4/13	Valley Middle School	Grand Forks, ND
4/19	Schroeder Middle School	Grand Forks, ND
4/20	Clearwater County Commission Meeting	Bagley, MN
4/20	Golden K – Kiwanis Meeting	Fargo, ND
4/26	RRBC Water Quality Meeting	Moorhead, MN
4/28	Golden K – Kiwanis meeting	Wahpeton, ND
5/17	City Council Meeting	Grand Forks, ND
5/18–5/19	Geographic Information System (GIS) Conference	Nashville, TN
5/20–5/21	Legislative Forum	Fargo, ND
5/20	County Commission Meeting	Valley City, ND
6/03	Nelson County Commission Meeting	Lakota, ND
6/04	Griggs County Commission Meeting	Cooperstown, ND
6/07	City Council Meeting	Valley City, ND
6/15	Ransom County Commission Meeting	Lisbon, ND

6/15	Sargent County Commission Meeting	Forman, ND
6/21	Cass County Commission Meeting	Fargo, ND
6/22	Polk County Commission Meeting	Crookston, MN
6/24	Waffle AAB Meeting	Grand Forks, ND
6/29	Roseau County Commission Meeting	Roseau, MN
6/29	Clearwater County Commission Meeting	Bagley, MN
7/06	Trail County Commission Meeting	Hillsboro, ND
7/20	Pembina County Commission Meeting	Cavalier, ND
7/20	Walsh County Commission Meeting	Grafton, ND
7/26–7/28	Soil and Water Conservation Society Conference	St. Paul, MN
8/03	Steele County Commission Meeting	Finley, ND
8/04	Grand County Commission Meeting	Elbow Lake, MN
8/10	WDAZ Channel 8 Interview	Grand Forks, ND
8/10	Clay County Commission Meeting	Moorhead, MN
8/10	Pennington County Commission Meeting	Thief River Falls, MN
8/11	Red River Farm Network Interview	
8/12	KNOX Radio Interview	EERC
8/16	KFGO Radio Interview	
8/17	Kittson County Commission Meeting	Hallock, MN
8/17	Marshall County Commission Meeting	Warren, MN
8/24	Red Lake County Commission Meeting	Red Lake Falls, MN
8/26	CAB Meeting	Grand Forks, EERC
9/7	Ottertail County Commission Meeting	Fergus Falls, MN
9/21	Mahnomen County Commission Meeting	Mahnomen, MN
9/23	Norman County Commission Meeting	Ada, MN
10/12	Wilkin County Commission Meeting	Breckenridge, MN
11/01–11/04	American Water Resources Association (AWRA) Annual Meeting	Orlando, FL
11/02	Beltrami County Commission Meeting	Bemidji, MN
11/09	Becker County Commission Meeting	Detroit Lakes, MN
11/16	Traverse County Commission Meeting	Wheaton, MN
11/19	Conservation Easement Assessment Program Meeting	Washington, DC
11/22	Future Farmers of America (FFA) Presentation	Mahnomen, MN
11/29	Marshall, Polk, Pennington and Beltrami County Ditch Authority Board Meeting	Grygla, MN
12/2	U.S. Environmental Protection Agency	Washington, DC
12/7	Fosston High School Agricultural and Science Class	Fosston, MN
12/14	Park River High School Future Farmers of America (FFA) Class	Park River, ND
12/15–12/16	MN State Conservationist	Minneapolis, MN
Date (2003)	**Meeting Attendance/Presentations**	**Location**
	Minnesota Society of Professional Engineers	Minneapolis, MN
	UND Geography Department Forum	Grand Forks, ND
	Prairie Public Television Interview	Grand Forks, ND
	Canadian Broadcasting Interview	
	Winnipeg Free Press Interview	Winnipeg, MB
1/7	Roseau River WD Meeting	Roseau, MN
1/15–1/17	RRBC Conference	Winnipeg, MB
1/24	Cass County WRB Meeting	West Fargo, ND
1/27	Middle-Snake Rivers WD Meeting	Warren, MN

1/28	Pembina County WRB Meeting	Cavalier, ND
2/4	Steele County WRB Meeting	Finley, ND
2/4	Two Rivers WD Meeting	Hallock, MN
2/5	Grand Forks County WRB Meeting	Grand Forks, ND
2/10	Barnes County WRB Meeting	Valley City, ND
2/11	GF Chamber of Commerce Agribusiness Committee	Grand Forks, ND
2/18	Trail County WRB Meeting	Hillsboro, ND
2/20	Sargent County WRB Meeting	Forman, ND
2/25	Walsh County WRB Meeting	Grafton, ND
2/27	Nelson County WRB Meeting	Lakota, ND
3/4	Sandhill River WD Meeting	Fertile, MN
3/19	Minnesota Society of Professional Engineers	Minneapolis, MN
3/20	Bois De Sioux River WD Meeting	Wheaton, ND
3/25	Walsh County WRB Meeting	Grafton, ND
4/16	Ransom County WRB Meeting	Lisbon, ND
4/23–4/24	2003 International Water Conference: Water, Science, and Decision-Making	Moorhead, MN
5/13	Trail County SCD Meeting	Hillsboro, ND
5/15	Concerned Citizens' Group Meeting	Ada, MN
6/9 – 6/11	Iowa National Watershed Conference	Council Bluffs, IA
6/10	Cavalier County SCD Meeting	Langdon, ND
6/12	Polk County SWCD Meeting	McIntosh, MN
6/16	Pennington County SWCD Meeting	Thief River Falls, MN
6/24	Beltrami County SWCD Meeting	Grygla, MN
6/24	Waffle CAB Meeting	Grand Forks, ND
6/30	Griggs County SCD Meeting	Cooperstown, ND
7/2	Nelson County SCD Meeting	Lakota, ND
7/3	Traverse County SWCD Meeting	Wheaton, MN
7/8	Wilkin County SWCD Meeting	Breckenridge, MN
7/8	Richland County SCD Meeting	Morton, ND
7/10	Steele County SCD Meeting	Finley, ND
7/15	Marshall County SWCD Meeting	Warren, MN
7/15	Norman County SWCD Meeting	Twin Valley, MN
7/16	Ransom County SCD Meeting	Lisbon, ND
7/17	Conservation Reserve Enhancement Program Meeting	Crookston, MN
7/23	Wildrice River WD Tour	Ada, MN
7/24	Polk County SWCD Meeting	Crookston, MN
8/5	Griggs County FSA Meeting	Cooperstown, ND
8/5	Grand Forks County FSA Meeting	Grand Forks, ND
8/13	Traill County FSA Meeting	Hillsboro, ND
8/13	Pembina County SCD Meeting	Cavalier, ND
8/13	Cass County FSA Meeting	Fargo, ND
8/14	Kittson County SWCD Meeting	Hallock, MN
8/14	Clay County SWCD Meeting	Moorhead, MN
8/19	Mahnomen County SWCD Meeting	Mahnomen, MN
8/19	Cass County SCD Meeting	Fargo, ND
8/20	Becker County SWCD Meeting	Detroit Lakes, MN
8/20	Beltrami County FSA Meeting	Bemidji, MN

8/21	Clearwater County SWCD Meeting	Bagley, MN
8/22	KRJB Radio Interview	Ada, MN
8/25	Richland County WRB Meeting	Whapeton, ND
8/26	Becker County FSA Meeting	Detroit Lakes, MN
8/27	Mahnomen County FSA Meeting	Mahnomen, MN
8/28	Waffle Public Meeting	Ada, MN
9/4	Norman County FSA Meeting	Ada, MN
9/9	Ottertail County FSA Meeting	Fergus Falls, MN
9/16 – 9/19	The Use of GIS and Remote Sensing in Water Resources, Hydrology, and the Environment Conference	Yichang, China
10/3	Freshwater Institute Meeting	Winnipeg, MB
10/8	Roseau County FSA Meeting	Roseau, MN
10/8	INGEOS (Indians in the Geologic Sciences)	Grand Forks, ND
10/14	Ottertail County SWCD Meeting	Fergus Falls, MN
10/15	Red Lake DNR and Red Lake Tribal Council Meeting	Red Lake, MN
10/20	Red Lake County SWCD Meeting	Red Lake Falls, MN
10/21	Barnes County SCD Meeting	Valley City, ND
10/28	Traill County FSA Meeting	Hillsboro, ND
10/30	Waffle AAB Meeting	Grand Forks, ND
11/5	Polk County FSA Meeting	Crookston, MN
11/5	Waffle CAB Meeting	Grand Forks, ND
11/6	Richland County FSA Meeting	Wahpeton, ND
11/10	Grand Forks County Extension Services Multiple Township Boards Meetings	Larimore, ND
11/12	Clay County FSA Meeting	Moorhead, MN
11/20	Barnes County Township Board Meeting; North Dakota Extension Services	Valley City, ND
11/25	Griggs County Extension Service Township Meeting	Cooperstown, ND
11/25	Trail County Extension Service Township Board Meeting	Hillsboro, ND
11/26	Reynolds Marketing Club Meeting	Reynolds, ND
12/9	Steele County Township Boards Meeting	Finley, ND
12/11	Walsh County SCD Meeting	Park River, ND
Date (2002)	**Meeting Attendance/Presentations**	**Location**
	Administrator of the Wild Rice WD	Ada, MN
	RRBC Monthly Meeting	Grand Forks, ND
	RRBC DEM Meeting	Fargo, ND
	ND Association of Water Resources Boards	Bismarck, ND
	RRBC	Grand Forks, ND
	GIS Day, UND Geology Department	Grand Forks, ND
	KCNN “Hot Talk” Interview	Grand Forks, ND
	Great Western Exchange Club	Grand Forks, ND
	KCNN “Hot Talk” Interview	Grand Forks, ND
	International Red River Board 3rd Annual Meeting	Detroit Lakes, MN
	ND Public Radio News Broadcast Interview	Fargo, ND
	KVLY News Broadcast	Grand Forks, ND
	KSTP TV News Broadcast	Minneapolis, MN
	WDAZ News Broadcast	Grand Forks, ND
	KVLY News Broadcast	Grand Forks, ND
	Red River Farm Network News Broadcast	Grand Forks, ND

	KCNN “Hot Talk” Interview	Grand Forks, ND
	KNOX Talk Show	Grand Forks, ND
	South Forks Lions Club	Grand Forks, ND
	Red River Water Management Board Meeting	Winnipeg, MB
	Canadian Water Resources Association Conference	Winnipeg, MB
	International Red River Board Annual Meeting	Detroit Lakes, MN
	RRBC Annual Meeting	Devils Lake, MN

APPENDIX F

WAFFLE LANDOWNER SURVEY

the Waffle®

Landowner Survey

We need your opinion on flood management practices!

☑

Energy & Environmental Research Center®

University of North Dakota

Energy & Environmental Research Center
15 North 23rd Street
PO Box 9018
Grand Forks, ND 58202-9018

PRESORTED
STANDARD
U.S. POSTAGE PAID
Grand Forks, ND
58202
PERMIT NO. 10

Energy & Environmental Research Center
15 North 23rd Street
PO Box 9018
Grand Forks, ND 58202-9018

March 10, 2005

Dear Landowner:

The Energy & Environmental Research Center (EERC) needs your help. We invite you to take part in a survey to determine issues that are important to landowners regarding water management and flood mitigation within the Red River Basin. Your input is an extremely important part of our research, **and your answers will remain anonymous**. The following addresses some questions you may have regarding this survey:

- ***What's in it for me?*** For returning the survey, all survey respondents will automatically be entered into a drawing to win a digital camera; gift certificate to a sporting goods store, department store, or restaurant; or a waffle iron. Your survey answers will provide information to direct future research. Results of the survey will be available to you upon request.

- ***How long will it take me to complete the survey?*** 10 to 15 minutes.

- ***What will you do with my answers?*** EERC and North Dakota State University (NDSU) researchers will use the information from the survey to incorporate landowner perspective into their research on water management and flood mitigation practices. Information you provide will not be attributed to you in any results reported as part of the research.

- ***Where can I get more information?*** Call me at 701-777-5185, write me at the EERC address above, or e-mail me at shanson@undeerc.org.

Thank you for helping us with this important research!

Sincerely,

Sheila Hanson

Sheila K. Hanson, Ph.D.
Marketing Research Manager

SKH/jdk

Enclosure

Landowner Survey

The Energy & Environmental Research Center (EERC) at the University of North Dakota in Grand Forks is studying potential solutions to flooding issues in the Red River Basin. Learning from landowner experience is a key component of our study. As part of our effort, we would appreciate your input and recommendations.

Please take a few minutes to complete the following questions. The completed form may be returned postage paid to the EERC.

1. Which of the following best describes you:
   - ☐ Landowner
   - ☐ Landowner and producer
   - ☐ Producer

2. Please list, by township and county, the acreage you own and rent:

a. Township	b. County	c. Acreage	d. Own or Rent
1. ____________________	____________	____________	☐ Own or ☐ Rent
2. ____________________	____________	____________	☐ Own or ☐ Rent
3. ____________________	____________	____________	☐ Own or ☐ Rent
4. ____________________	____________	____________	☐ Own or ☐ Rent
5. ____________________	____________	____________	☐ Own or ☐ Rent
6. ____________________	____________	____________	☐ Own or ☐ Rent

3. Please describe your overall farming operation:

   a. ______Number of acres in production agriculture
   b. ______Number of acres of land leased out to another party
   c. ______Number of acres in CRP or related programs
   d. ______Other (please describe:________________________________)
   e. ______Total acres

4. What crops do you produce?

   a. ☐ Barley
   b. ☐ Corn
   c. ☐ Dry edible beans
   d. ☐ Durum wheat
   e. ☐ Flax
   f. ☐ Hard red spring wheat
   g. ☐ Oats
   h. ☐ Potatoes
   i. ☐ Sugar beets
   j. ☐ Sunflowers
   k. ☐ Soybeans
   l. ☐ Other ________________

5. Have you ever irrigated any of your land? ☐ Often ☐ Occasionally ☐ Never
   If so, please describe____
   ____
   ____

Landowner Survey

6. Have you ever collected insurance for flood loss on your agricultural land?

a) Spring flood loss ☐ Yes ☐ No
b) Summer flood loss ☐ Yes ☐ No

7. Have you received financial support from any state or federal agency to implement soil and/or groundwater protection on this land? ☐ Yes ☐ No

8. Have you received technical assistance from any state or federal agency to implement soil and/or groundwater protection on any of your land? ☐ Yes ☐ No

9. Please rate each of the following issues from 1 to 5, where 1 is a high priority and 5 is a low priority.

	High Priority				Low Priority	No Opinion
a) Improve water quality in our local rivers and streams	1	2	3	4	5	0
b) Reduce flooding problems	1	2	3	4	5	0
c) Reduce stream bank erosion	1	2	3	4	5	0
d) Increase wetland protection	1	2	3	4	5	0
e) Increase education on environmental issues	1	2	3	4	5	0

10. Have you ever held back water on any of your land for any reason? ☐ Yes ☐ No

If yes, please describe ______________________________

____

____

11. Do you ever experience problems with flooding on any of your land?

☐ Spring
☐ Summer
☐ Both spring and summer
☐ No problems
☐ Other (list)

12. If you experience spring flooding on your land, how would you best describe your "typical" year?

☐ Yes, spring flooding on some tracts
☐ Yes, spring flooding on all tracts
☐ No, I rarely have spring flooding problems (please skip to Question 15)

13. Aside from weather events, what do you believe causes spring flooding on your land? (mark all that apply)

a. Upstream water release ☐ Yes ☐ No
b. Overland flooding ☐ Yes ☐ No
c. Water course channels are too small ☐ Yes ☐ No
d. Neighbor modifying runoff patterns ☐ Yes ☐ No
e. Culverts are sized wrong ☐ Yes ☐ No
f. Uncertain of causes ☐ Yes ☐ No
g. Comments: ______________________________

____

____

____

Landowner Survey

14. When there is a substantial spring flood in the Red River Valley, what type of additional planting or spring field work delays do you typically experience on your land? (Note: we are referring to delays beyond when you start field work in a normal year).

- ☐ No delays, land does not typically flood.
- ☐ Typically I'm delayed less than 1 week.
- ☐ Typically I'm delayed between 1 and 2 weeks.
- ☐ Typically I'm delayed between 2 and 3 weeks.
- ☐ Typically I'm delayed between 3 and 4 weeks.
- ☐ In bad flood years, I am often prevented from planting a crop.

15. What do you believe are useful solutions for spring flooding problems in the Red River Basin? Please rate each on a scale of 1 to 5, where 1 indicates very useful and 5 indicates not useful.

Structural Measures	Very Useful				Not Useful	No Opinion
a. Dams and reservoirs	1	2	3	4	5	0
b. Impoundments	1	2	3	4	5	0
c. Diversion channel	1	2	3	4	5	0
d. Floodway or greenway	1	2	3	4	5	0
e. Channelization (straightening natural waterways)	1	2	3	4	5	0
f. Levees and dikes	1	2	3	4	5	0
g. Ring dikes	1	2	3	4	5	0
h. Placement of surface drainage ditches	1	2	3	4	5	0
i. Improvement of existing surface drainage ditches	1	2	3	4	5	0
j. Placement of subsurface drainage tiles	1	2	3	4	5	0
k. Improvement of existing subsurface drainage tiles	1	2	3	4	5	0

Nonstructural Measures	Very Useful				Not Useful	No Opinion
l. Temporary water retention using private lands	1	2	3	4	5	0
m. Temporary water retention using public lands	1	2	3	4	5	0
n. Dry dams	1	2	3	4	5	0
o. Wetland restoration	1	2	3	4	5	0
p. Restoring natural waterways	1	2	3	4	5	0
q. No-till agriculture	1	2	3	4	5	0
r. Ice control management	1	2	3	4	5	0
s. Stream maintenance	1	2	3	4	5	0
(clearing brush, trees, blockages, dredging)	1	2	3	4	5	0
t. Ditch maintenance	1	2	3	4	5	0

16. Do you have any additional thoughts to share for the best solution(s) for the public at large to deal with spring flooding in the Red River Basin? ____

____

____

____

____

____

____

____

____

17. Please select the level of risk that you believe exists for a significant spring flooding event to occur in the Red River Basin in the next 50 years. Examples of significant years of spring flooding include 1950, 1979, and 1997.

☐ High risk ☐ Considerable risk ☐ Some risk ☐ Little risk ☐ No risk

Brief Description of Waffle Project:
The Waffle project would use both nonagricultural and agricultural land to temporarily store water early in the spring to slow the rate of runoff into tributaries and rivers in the Red River Basin. Initial research at the EERC at UND has indicated that if a Waffle-based program had been implemented prior to the 1997 flood, the severity of that flood would have been substantially reduced. Participation in the Waffle program would be voluntary; however, if water were stored on agricultural land, some minimal planting delays might occur in years when the Red River Basin is subject to widespread flooding. Although it's difficult to predict how often the Waffle would be used or precisely how long water would remain on the land, it is reasonable to anticipate that the Waffle would be used only during years when a major spring flood event is probable and that water storage might last anywhere from a few days to as much as 2 weeks after snowmelt.

18. Based on the information above, please rate your responses to the following statements.

	Strongly Agree		Neutral		Strongly Disagree
a. I would consider enrolling some of my land if compensated in an acceptable manner.	1	2	3	4	5
b. I would never consider enrolling any of my land in the program.	1	2	3	4	5
c. I would only consider enrolling if my neighbors also agreed to enroll their land.	1	2	3	4	5
d. I feel well informed about the Waffle Concept.	1	2	3	4	5

19. Had you ever heard or read anything about the Waffle project prior to receiving this survey?

☐ Yes ☐ No (if no, skip to Question 21)

20. If yes, in which of the following sources have you gained information about the Waffle project? (mark all that apply)

a. ☐ Neighbors (word of mouth)
b. ☐ Newspaper articles
c. ☐ Television
d. ☐ Radio
e. ☐ Producer meetings/workshops
f. ☐ Extension/university mailings
g. ☐ Internet/World Wide Web
h. ☐ Others ________________

21. What kind of information would be helpful to you to consider temporary water storage on your land as a potential spring flood management practice in the Red River Basin? ____________________________________

____

____

____

22. Do you have any questions or concerns that you would like to share or see addressed by the Waffle project now or in the future? ____

____

____

23. The following is a hypothetical example to estimate how much it might cost to enroll land in a program like the Waffle. Please consider the following conditions before responding to the question:

- Assume participation in the Waffle is based on landowner bids and would require you to enroll your land for a period of 10 years.
- Assume you would receive an initial enrollment payment plus a payment each year that the Waffle temporarily stored water on your land.
- Assume you do not have to enroll all of your land, as only a limited amount of agricultural land in the Red River Basin would be required for the program.
- Assume participation in the Waffle would not affect your coverage in Federal Crop Insurance.

Please note: your bids are not binding, this is just a hypothetical situation.

Given the above example,

☐ Yes, I would consider participation.

a. With a 1-week planting delay, I would need $________/acre to participate.
b. With a 2-week planting delay, I would need $________/acre to participate.
c. With a 3-week planting delay, I would need $________/acre to participate.
d. If I were prevented from raising a crop in a flood year, I would need $_______/acre to participate.

☐ No, I would not participate regardless of the level of compensation.

24. How long have you lived in the Red River Basin area? _____ years

25. What is your age category? ☐ 18–34 ☐ 35–44 ☐ 45–54 ☐ 55–64 ☐ 65 +

26. What is your gender? ☐ Male ☐ Female

27. Please provide the following confidential information to be entered in our drawing for the digital camera, gift certificates, and waffle iron:

Name: ____________________

Address: ____________________

City, State, Zip: ____________________

E-mail: ____________________

28. Would you like to receive information on the Waffle Research Study? ☐ Yes ☐ No

If you have any questions or additional comments regarding this survey, please contact:

Sheila Hanson
Marketing Research Manager
Energy & Environmental Research Center
PO Box 9018
Grand Forks, ND 58202-9018
Phone: (701) 777-5185
E-mail: shanson@undeerc.org

www.undeerc.org

UNIVERSITY OF
NORTH DAKOTA

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

BUSINESS REPLY MAIL

FIRST-CLASS MAIL PERMIT NO. 225 GRAND FORKS, ND

POSTAGE WILL BE PAID BY ADDRESSEE

4650-0997
The Energy & Environmental Research Center
UNIVERSITY OF NORTH DAKOTA
PO BOX 7053
GRAND FORKS ND 58202-9988

Attn: Sheila Hanson

Please fold on the dashed line, secure end and mail.

Your contribution to this research is greatly appreciated.

Thank you!

Please return your postage paid questionnaire by folding it in half, sealing with tape or staple, and dropping it in the nearest mailbox.

APPENDIX G

WILD RICE WATERSHED LANDOWNER SURVEY RESULTS

LANDOWNER OPINION OF FLOOD MANAGEMENT PRACTICES IN THE RED RIVER BASIN – THE WILD RICE WATERSHED IN MINNESOTA

INTRODUCTION

The goal of the Wild Rice Watershed landowner mail survey was to conduct exploratory research into existing and potential flood management practices in the Red River Basin (RRB). Since public opinion is key to implementing any flood mitigation strategy, landowners are an important element in the RRB system. The survey questions were attitudinal in nature. Some questions relied on respondents to predict their future interest or behavior. The survey employed open- and closed-ended questions to gather both qualitative and quantitative information.

Adoption of new practices depends on the willingness of producers to alter their current management and production practices. A change in one component of a practice will likely impact other components of the farming systems. This pilot study in the Wild Rice Watershed begins at the attitudinal level with such measures as perceived risk of future flooding, consideration of participation in a future temporary storage program, and perceived usefulness of structural and nonstructural flood control measures.

This pilot study precedes a more comprehensive study of 15,000 surveys, mailed to a random sample of landowners and producers throughout the RRB. Several of the questions developed in the pilot study will be included in the basinwide survey, along with newer questions to address issues raised by landowners, including the socioeconomic aspects of a potential Waffle® program.

Tradition is important. Sometimes it is challenging to implement a practice that is different than that practiced by generations of families. The respondents to this exploratory study were challenged to consider a relatively new concept, the Waffle, which parts from tradition but provides a potential solution to a long-standing problem—flooding in the RRB.

The Waffle is a multiyear project being conducted by the University of North Dakota Energy & Environmental Research Center (EERC). After the 1997 spring flood, the EERC sought funding to determine the feasibility of temporarily storing water in rural ditches and fields bounded by raised roads to augment existing flood control structures and help mitigate flooding throughout the RRB. Funding for this project was allocated by Congress and administered through the U.S. Department of Agriculture Natural Resources Conservation Service in 2002.

METHODS

Landowner names and mailing lists for the Wild Rice Watershed (see Figure 1 for map) were obtained from the county auditors in Becker, Clearwater, Mahnomen, and Norman Counties (all in Minnesota). Within those counties, 64 townships were represented. Since the research instrument was a mail survey, which often has response rates of under 5%, it was decided to send the survey to the entire population of 4831 landowners, defined as those landowners accurately identified and accounted for in the county auditor's database. Since many addresses were undeliverable, the actual population count was 4702. A questionnaire was developed to learn about landowner opinion initially in the Wild Rice Watershed, as that was also the location of an initial Waffle field trial. A pilot landowner survey was conducted with several landowners in Grand Forks (North Dakota) and

Figure 1. Map of Wild Rice Watershed within the RRB.

Polk Counties to ensure that the questions and answers were both understandable and relevant. This process was helpful for insight into landowners' level of understanding of the survey questions and their opinion on the survey length and survey design. The response rate was 11.5%, comprising 542 surveys. This provided sufficient sample size for descriptive statistics and some group comparisons.

PERCEIVED RISK

Humanity is at risk from a wide variety of natural disasters. Floods, earthquakes, landslides, tornadoes, tsunamis, and volcanoes strike focused geographical areas. Others, such as droughts and hurricanes, can affect larger regions. Most of these natural disasters impact human populations regularly when viewed on the continental or global scale, although the odds of their happening in any one place in any one year are relatively low.

Americans have always feared floods, and with good reason (Haeuber and Michener, 1998). Floods are the most common and costly large natural disturbances affecting the United States. Approximately nine of every ten presidential disaster declarations are the result of floods. Floods took more than 200 lives between 1990 and 1995, and total flood damage costs between 1990 and 1997 reached nearly $34 billion (Haeuber and Michener, 1998).

In the survey, respondents were asked to select the level of risk that they believe exists for significant spring flooding to occur in the RRB in the next 50 years. An important consideration in understanding the landowners in the RRB is to gauge their opinion of their present environment and future risks. Figure 2 shows the respondents' perceived risk of spring flooding from high risk to no risk.

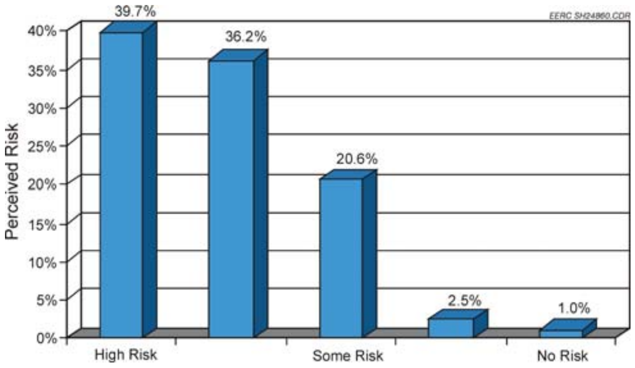


Figure 2. Perceived risk.

When asked about the level of risk that they believe exists for significant spring flooding to occur in the RRB in the next 50 years (examples of significant years of spring flooding include 1950, 1979, and 1997), the top two bars total 75.9%, which one could interpret as a sample of landowners who feel at risk of future flooding (see Figure 2).

"For four decades, social scientists have been studying how and why people respond to information and warnings about the risk of various natural disasters." Yet relatively little evidence exists on which to build a description of the basic social process that occurs between people's perception of risk and inclination to take action (Mileti et al., 1992).

STRUCTURAL/NONSTRUCTURAL MEASURES

The earliest approaches to floodplain management in the United States focused on structural measures to keep floodwaters away from existing or proposed developments. These measures included levees (dikes), floodwalls, channel improvements, and dam–reservoir systems. In the wake of a devastating flood in 1927, the 1936 Flood Control Act shifted flood control responsibility primarily to the federal government and provided a national program for implementing these structural measures (Sheaffer et al., 2002). An evaluation of this program after 20 years concluded that flood damage continued to increase nationally. To create a comprehensive floodplain management program, nonstructural dimensions are needed to supplement the structural measures (Sheaffer et al., 2002).

In order to assess landowner opinion regarding the usefulness of structural and nonstructural measures for flood mitigation, they were asked the following question: "What do you believe are useful solutions for spring flooding problems in the Red River Basin? Please rate each on a scale of 1 to 5, where 1 indicates very useful and 5 indicates not useful" (see Figures 3 and 4).

The structural and nonstructural measures were combined and reduced to a top five list of the most useful flood mitigation measures according to landowners in the Wild Rice

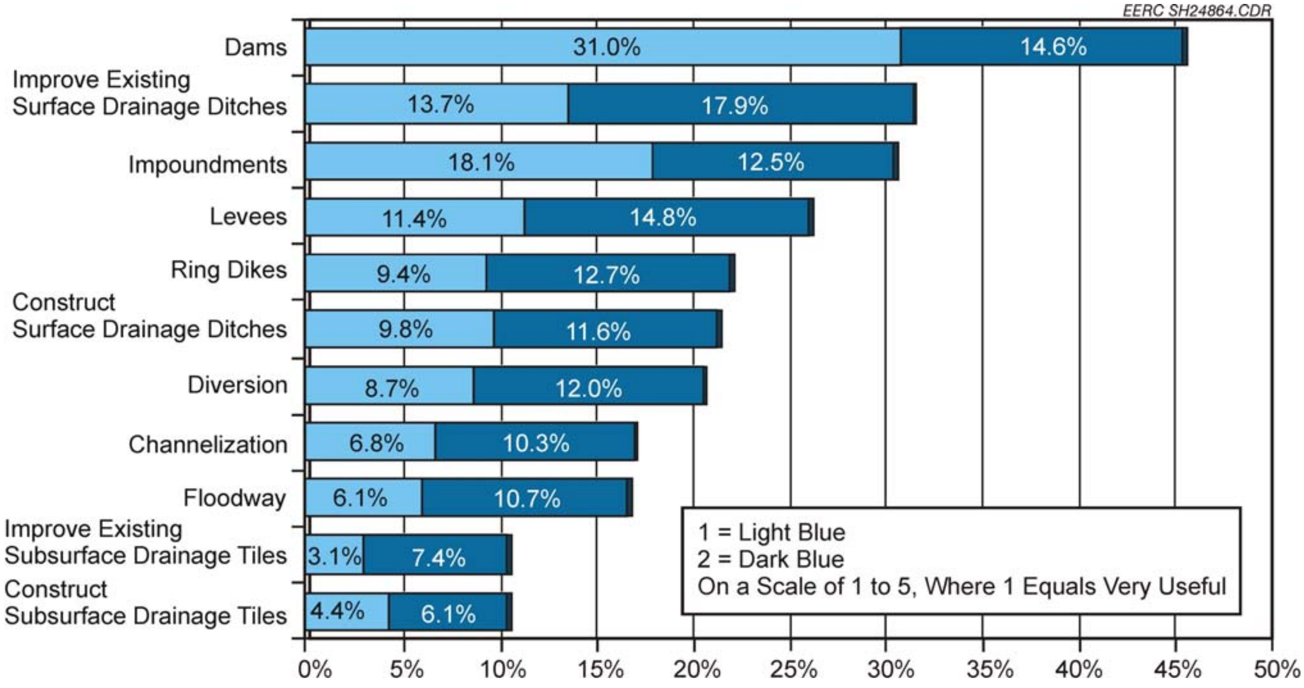


Figure 3. Structural measures.

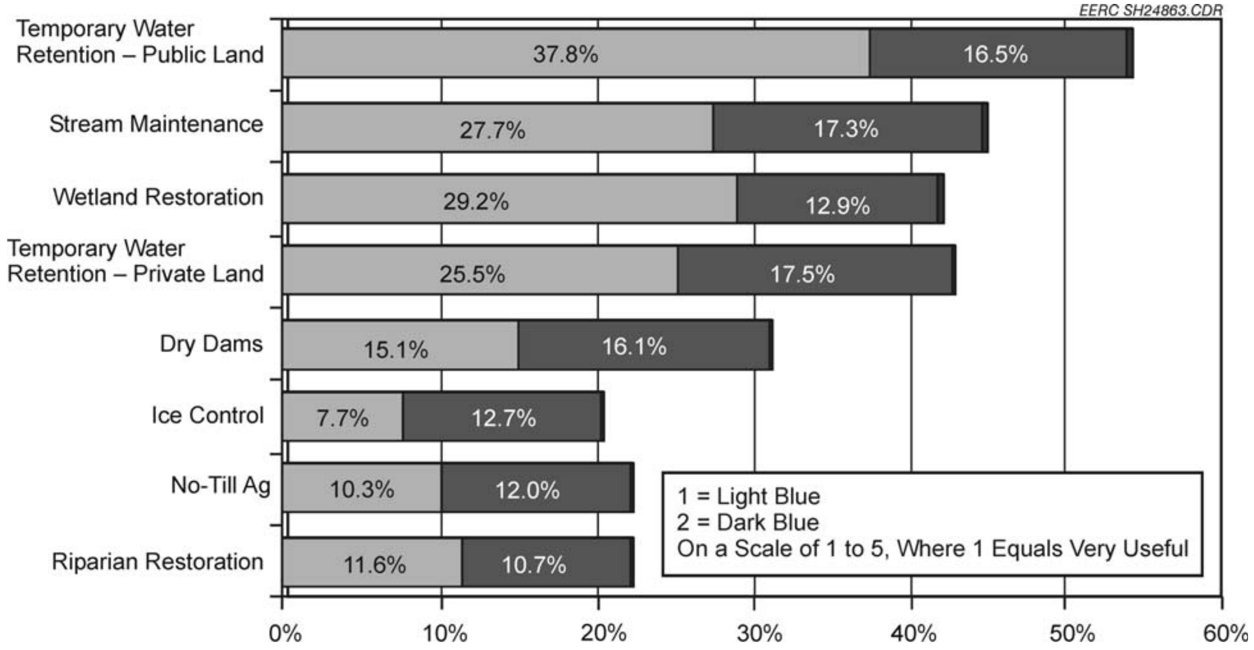


Figure 4. Nonstructural measures.

Watershed. The data were collapsed into a single “useful” category, comprising of those who indicated a 1 or a 2 on the scale of 1 to 5. The top five measures are temporary water retention on public land, dams, stream maintenance, temporary water retention on private land, and wetland restoration. The top five list, as summarized in Figure 5, consists of nonstructural measures, with the exception of dams.

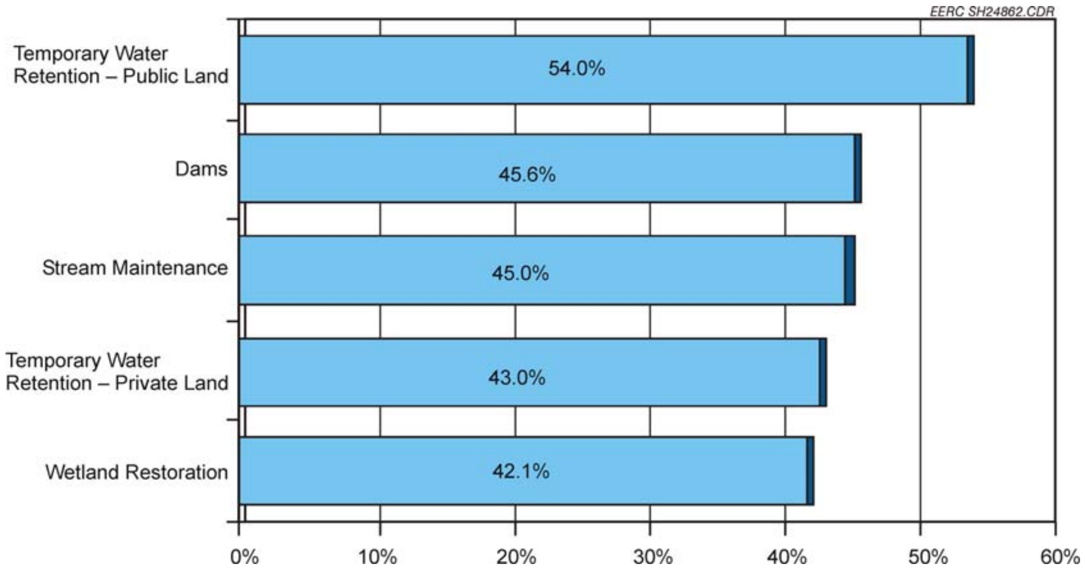


Figure 5. Top five flood mitigation measures.

Temporary water storage on public land (54.0%) and temporary water storage on private land (43.0%) both encompass the Waffle concept. As such, one could infer that those who find temporary water retention measures useful may also find the Waffle concept to be a useful means of flood mitigation.

EXISTING CONDITIONS FOR LANDOWNERS

Flooding Experiences

Of the respondents, 66.5% have experienced flooding on their land, while 33.5% have experienced no flooding on their land. Spring and summer are both seasons of concern for flooding, as listed in Table 1. Various causes for the flooding were given, with the top answer of overland flooding and other reasons listed in Table 2. Of the sample, 48.4% own land that is adjacent to a river, stream, creek, or drainage system that creates flooding problems.

Table 1. Experienced Problems with Flooding on Their Land

Response	Percentage
Spring	11.2
Summer	3.0
Both	49.6
No Problems	33.5
Total	100.0

Table 2. Perceived Non-Weather-Related Causes of Spring Flooding on Their Land

Response	Percentage
Overland flooding	33.2
Other	28.6
Culverts are sized wrong	21.4
Neighbor modifying runoff patterns	20.8
Upstream water release	19.6
Watercourse channels are too small	18.6

Note: Multiple response question, so totaling percentage of responses exceeds 100%.

The "other" category included responses such as dams, beavers, ice jams on the Wild Rice River, and blockage of ditches. Although this study addresses only spring flooding, summer rains were also mentioned as a source of concern for flooding.

Holding Back Water

Survey respondents were asked if they have ever held back water for any reason, and 13.7% had done so. Those respondents were also asked for an open-ended explanation. Reasons offered included beaver dams, natural flooding already occurring on their land, erosion control, wetland and wildlife, planned flood prevention, drainage problems, and water held by roads. One interesting response was, "during the so-called Dirty Thirties, we dammed up any water we could to save water," dating back to times when droughts were a concern. Although droughts are not necessarily on everyone's mind now, they will return at some point, as a part of the cycle of flooding and drought in the RRB.

Participation in Programs

Adoption of a new program could likely be related to participation in other programs if one believes that past behavior predicts future behavior. The literature on the acceptance of new agricultural practices by landowners will be addressed in the larger basinwide study, although it appears at this time that no strong models exist. As exemplary of participation in existing programs, 19.7% of the sample had participated in Conservation Reserve Program (CRP) or related programs. 7.7% have received financial support from state or federal agency to implement soil and/or groundwater protection on their land, and 7.1% have received technical assistance from a state or federal agency to implement soil and/or groundwater protection on their land.

INFORMATION SOURCES

An ongoing debate in attitude–behavior research has concerned the relationship of attitudes to behavior and the extent to which, through knowing an individual's attitudes, one is able to predict that individual's behavior. Although the debate has not produced a definite answer or a unified theory, the consensus is that a relationship exists. However, social–psychological research reveals that attitudes, by themselves, are not sufficient predictors of behavior. Other factors need to be examined to understand this relationship. One of the most powerful intervening variables in the attitude–behavior relationship is that of social influences, such as situations, reference groups, and information sources (Petrzelka and Korsching, 1996).

Because of the exploratory nature of the study, a formal relationship between attitudes and information sources or outreach activities was not hypothesized at the outset of the study. The early questions in the survey asked for opinions without addressing the specifics of a potential "temporary water storage program." Although a specific Waffle program description was not provided in this survey, later in the survey respondents were asked if they would be interested in learning more about the Waffle study as described toward the latter portion of the survey; 63.4% indicated interest.

LANDOWNER-GENERATED OPINIONS FOR POTENTIAL SOLUTIONS

As a purely open-ended question, landowners were asked to state what they felt would be a reasonable solution to springtime flooding. Responses ranged from optimistic to pessimistic, and some were idealistic. Here are some examples of landowner-provided solutions:

Most Optimistic Responses

- "If there would be some way to hold back some of the water so it would not come so fast."
- "I think a combination of floodways, channels, and reservoirs and temporary retention would help."
- "Slow the rush of water to the river."
- "Think ahead every spring."
- "Sound development plans with both nonstructural and structural measures and value wetlands."
- "If we can pipe oil from Alaska, why can't we pipe water from areas of excess to drought areas? Expensive, but we are repeatedly paying huge sums of money for disaster relief."

Least Optimistic Responses

- "Move to higher ground."
- "Uncontrollable. Past history shows it. "
- "When you are in Lake Agassiz, you should expect to get flooded. It's not our fault. "
- "In a floodplain there's flooding to one degree or another. There is no solution! Sorry."
- "It is hard to find good areas for water retention. As in my case, I don't have any place to store water because of the contour of the land."

Overall themes for many respondents included the idea of planning and coordination, slowing the rush of water, utilizing multiple methods to provide solutions, and for others a sense of loss of control and giving up the idea of human solutions to the forces of nature.

As stated by Korsching et al. (2001), "interests are largely determined by the perceived benefits and costs of the problem and its resolution, along with the degree to which the existing condition and the perceived change are valued." There is no single public interest on which all residents of a community, township, county, or region will agree.

POTENTIAL PARTICIPATION

A key result is the attitudinal measure of participation. Potential participation was measured as the opinion toward "voluntary participation in a future program for temporary water storage on your land as a potential spring flood management practice in the Red River Basin?" The responses ranged from 1, "yes, would definitely consider," to 5, "no, would not consider."

It is important to note that the 16.8% of respondents did not indicate an opinion on the above question. That is understandable, given that the description of the Waffle concept provided to them was not specific as to the nature of the potential "future program." So, the above responses are based on a subset of 83.2% of the overall sample.

Although 36.3% stated that they would not consider temporary storage on their land, many listed explanations demonstrated that the respondent was not necessarily opposed to temporary water storage, but rather felt that their land was not appropriate for various reasons, such as:

- "As I mentioned—we are so flat and some distance from the beach (ridge) area—storage should be in that area."
- "Aside from the 8 acres I live on, my family and I own 240 acres of forested land that drains into the Red River System (in an unorganized trip)."

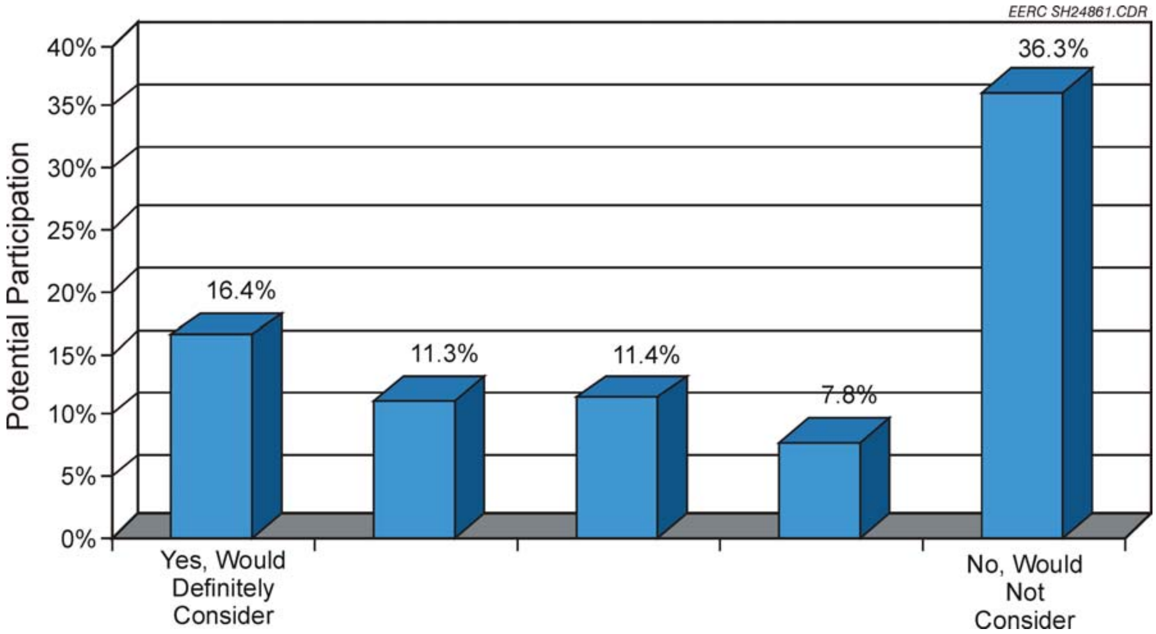


Figure 6. Potential participation.

- “My land is too elevated to store water.”
- “Definitely would consider if possible, however, my land is very elevated with sandy soil, and everything runs off.”
- “I live ¼ mile from the Continental Divide, so it would have no effect.”
- “If flooding lasted long enough to impair proper farming, then I would expect compensation.”

Previously, it was stated that temporary water storage on public land and temporary water storage on private land rated at 54.0% and 43.0%, respectively, in terms of perception of usefulness by landowners. The top two categories, the first two columns in Figure 5, indicating interest in participation in a program such as the Waffle, total 27.7%. This is lower than one might expect, given the perceived usefulness of temporary water storage indicated earlier.

To provide insight into this discrepancy in the findings, the open-ended follow-up response to interest in participation is helpful. Many of those who said that they would not consider the Waffle did not indicate that they did not support the Waffle concept; rather, they illuminated their answer by saying that their land would not be suitable for Waffle storage for reasons with the general themes of topography, close proximity to the river or other boundaries, and the need for compensation. Potential compensation was not provided as a hypothetical scenario in this survey, although it was formulated as a series of questions in the basinwide survey.

Finally, although a specific program description of the Waffle concept (currently a feasibility study) was not provided, respondents were asked if they would be interested in learning more about the study. To that question, 63.4% indicated interest.

VARIABLES RELATED TO POTENTIAL PARTICIPATION

Linking potential participation in a program to temporarily store water on their land to existing landowner conditions and their prior experience with flooding was part of the data analysis. For this analysis, the assumption was made that those answering 1 = Yes would definitely consider and 5 = No could be considered the current opinion leaders. For those respondents voicing a strongly positive or negative opinion, it is useful to consider which potential variables from existing conditions are related to their potential participation. The sample was further segmented into just the strong Yes (1) and strong No (5) categories.

Discriminant analysis is a statistical technique utilized to predict membership in a category based on their characteristics, which in this case was a combination of their attitudes and past experiences. To run the analysis, 232 cases were processed, and 71.1% were correctly predicted into the appropriate categories of 1 or 5 based on the information provided by the following variables: perceived risk, interest in information, past flooding on their land, participation in CRP or other related programs, held water in the past for some reason, and years in the basin. Perceived risk, interest in learning more and past experience holding water are the key contributing variables in this scenario.

GROUP DIFFERENCES – INTEREST IN PARTICIPATION

It is also helpful to consider the demographics and group differences by comparing the means for interest in participation. Interest in participation here is reported as the mean for each category. The scale was from 1 to 5, where 1 was yes, strongly consider, 5 was not to consider, and 3 was neutral. So, the lower the mean, the higher the tendency to participate.

Gender

Males' interest in participation produced a mean of 3.3, while females had a mean of 3.8 (Table 3).

Table 3. Participation by Gender

Gender	Mean	N	Std. Deviation
Male	3.3092	380	1.6292
Female	3.8474	59	1.6062
Total	3.3815	439	1.6346

Note: P ≤ .05

Years in Basin

Collapsing the number of years a landowner has lived in the RRB was grouped into two categories, 30 years and less or more than 30 years (Table 4). Those residing in the basin 30 years or less had a mean of 3.2, while those residing in the basin more than 30 years showed a mean of 3.5. So, perhaps, those younger individuals or those newer to the basin would be more amenable to participating in a program such as the Waffle.

Table 4. Participation by Years in Basin

Years in Basin -2	Mean	N	Std. Deviation
30 years or less	3.3092	380	1.6292
More than 30 years	3.8474	59	1.6062
Total	3.3815	439	1.6346

Note: P ≤ .05.

Acreage

No significant differences were found between interest in participation by landowners between the standard National Agricultural Statistics Service (NASS) groupings of acreage (Table 5).

Table 5. Participation by Acreage

NASS	Mean	N	Std. Deviation
1–9	3.5000	4	1.9149
10–49	2.9032	31	1.5991
50–179	3.5763	59	1.6422
180–499	3.4478	67	1.5791
500–999	3.9333	30	1.3113
1000–1999	3.4194	31	1.5226
2000 or more	3.3600	25	1.2871
Total	3.4575	247	1.5425

FUTURE EFFORTS

This survey was utilized as a pilot study toward a larger basinwide survey as described in the introduction to this paper. The existing survey results relied on many open-ended questions to better understand existing flood management practices, while the basinwide survey is more succinct in the question-and-response format, based on what was learned in the first survey. In the second survey, more attention is given to other issues of concern to the basin, including such areas as water quality and the economics of potential Waffle scenarios in the future. A related study is addressing the cost-benefit analysis of the Waffle concept and will include data from the basinwide survey. The results provided the research team insight into existing flood management practices and attitudes toward potential flood management practices.

REFERENCES

Haeuber, R.A., and Michener, W.K., 1998, Issues in science and technology: p. 74–80.

Korsching, P.F., Hoiberg, E.O., Bultena, G. L., and Padgitt, S.C., 2001, Soil erosion as a community issue—public perceptions at off-site impacts: Society and Natural Resources, v. 14, p. 67–76.

Mileti, D.S., Fitzpatrick, C., and Farhar, B.C., 1992, Fostering public preparations for natural hazards: Environment, v. 34, no. 3, p. 16–25.

Petrzelka, P., and Korsching, P., 1996, Journal of Environmental Education v. 28 no. 1, p. 38–45.

Sheaffer, J.R., Mullan, D.J., and Hinch, N.B., 2002, Encouraging wise use of flood plains with market-based incentives: Environment, v. 44 no. 1, p. 32–44.

CONTACT INFORMATION

Bethany Kurz
Phone: (701) 777-5050
E-Mail: bbolles@undeerc.org

Sheila Hanson
Phone: (701) 777-5185
E-Mail: shanson@undeerc.org

John Harju
Phone: (701) 777-5157
E-Mail: jharju@undeerc.org

Gerald Groenewold
Phone: (701) 777-5131
E-Mail: ggroenewold@undeerc.org

Energy & Environmental Research Center
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018
Fax: (701) 777-5181

Visit the EERC’s Web site at www.undeerc.org.

APPENDIX H

BENEFIT-COST ANALYSIS OF THE WAFFLE: INITIAL ASSESSMENT

(Note: This is a separate report (including appendices that was provided to the EERC by the Department of Agribusiness and Applied Economics at North Dakota State University)

Agribusiness and Applied Economics Report No. 603 June 2007

Benefit-cost Analysis of the Waffle®: Initial Assessment

Dean A. Bangsund
Eric A. DeVuyst
F. Larry Leistritz

Department of Agribusiness and Applied Economics
Agricultural Experiment Station
North Dakota State University
Fargo, North Dakota 58105

ACKNOWLEDGMENTS

Several people were helpful in providing data and information used in this study. Our appreciation and thanks are extended to

Richard Carlson (U.S. Army Corps of Engineers)
Jeffrey L. McGrath (U.S. Army Corps of Engineers)
Randy Coon (Agribusiness and Applied Economics, NDSU)

Thanks are extended to all the city and county employees who provided residential and commercial property value data.

Special thanks are extended to Bethany Kurz and Sheila Hanson, Energy & Environmental Research Center, University of North Dakota, for their assistance and support throughout the project.

Thanks are given to Edie Nelson for document preparation and to our colleagues for reviewing this manuscript.

Financial support was provided by the Energy & Environmental Research Center, University of North Dakota. We express our appreciation for their support.

A single copy of this publication is available free of charge. Please address your inquiry to: Department of Agribusiness and Applied Economics, North Dakota State University, PO Box 5636, Fargo, ND 58105-5636, phone (701-231-7441), fax (701-231-7400), or e-mail: ndsu.agribusiness@ndsu.edu. This publication is also available electronically at the following web site: http://agecon.lib.umn.edu/

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

APPENDICES

TABLE OF CONTENTS (continued)

List of Tables

List of Figures

List of Appendix Tables

List of Appendix Tables (continued)

List of Appendix Tables (continued)

Appendix Table | Page

List of Appendix Tables (continued)

List of Appendix Tables (continued)

List of Appendix Figures

Executive Summary

The Red River of the North has a long history of flooding. A host of physical characteristics, along with man-made factors, contribute to widespread flooding in the Basin. Historically, attempts to mitigate flood damage in the Basin have been limited to using dikes/levees and waterways/diversions. Generally, within the greater Red River Basin, other flood mitigation strategies are insufficient by themselves to make meaningful reductions in flood damages. Despite ongoing efforts to combat flooding in the Basin, spring flooding continues to cause damage and concern among the region's inhabitants.

Another option to mitigating flood damages in the Red River Basin is the concept of using hundreds or thousands of 'micro-basin' storage areas comprised of roads and adjacent lands throughout the region. The micro-basin concept would utilize roads and other existing structures to act as temporary barriers to contain snow melt and flood runoff on adjacent lands. Flood water would be managed through culvert modifications to temporarily store water on those lands. The goal of using micro-basin storage would be to contain a sufficient volume of water over a reasonable period in the spring to lower the flood crest heights on streams and rivers throughout the basin. Water contained in the micro-basins would be gradually released after the threat of flooding had subsided. The use of roads and adjacent lands within the basin to temporarily hold water during periods of spring flooding has been referred to as the Waffle. The purpose of this report was to examine the economic feasibility of using the Waffle to reduce flood damages in the Basin.

A benefit-cost analysis was conducted for the Waffle. Costs of implementing, maintaining, and operating the Waffle were estimated for a 50-year period. Benefits in this study were limited to mitigated flood damages (i.e., the difference between flood damage with and without the Waffle) from four urban areas in the Basin. Although not included, the Waffle would be expected to mitigate flood damages (benefits) in rural areas, farmsteads, and other communities in the region and generate environmental benefits, such as reduced soil erosion, reduced sediment loading in waterways, and subsoil and groundwater recharge. The results of the study represent a conservative assessment of the economic feasibility of the Waffle since only a subset of potential benefits was included.

The Energy & Environmental Research Center at the University of North Dakota provided data on the physical size of the Waffle, which included acreage of land suitable for use in the Waffle delineated by county, typography, and land use, as well as the number of sections of land and associated costs of modifying culverts for the Waffle. A cost model was developed which used physical data on Waffle size combined with other economic data to estimate various expenses associated with the Waffle. Specific expenses included enrollment costs, landowner payments, infrastructure modifications and installations, and maintenance and administrative overhead.

Much of the data used for the benefits component of the analysis came from flood-stage damage functions (FSDF), developed by the U.S. Army Corps of Engineers, for selected communities in the Basin. The FSDFs relate river crest heights with probability of occurrence and expected damages to residential and commercial properties and public infrastructure at various crest elevations. Damage estimates within the functions were adjusted to reflect current economic conditions pertaining to the aggregate real (i.e., adjusted for effects of inflation) value of property at risk of flooding and included adjustments for recent changes in permanent flood protection (e.g., new or higher dikes). Further adjustment to the functions was performed to project expected damages based on future population change and annual change in the real aggregate value of residential and commercial property from 2006 through 2055.

The benefits of the Waffle were estimated as the difference between flood damages with and without the Waffle for several flood events at selected locations in the Basin. The flood events modeled included the 1997 flood, and several derivatives of the flows present during the 1997 flood. The Energy & Environmental Research Center provided estimated crest heights at key locations on the Red River for the modeled flood events with and without the Waffle.

Change in crest heights due to the Waffle influenced the expected level of flood damages for various flood events. Integration of the FSDF was performed with and without the Waffle to estimate expected (i.e., probability weighted) annual flood damages from 2006 through 2055. The difference in the expected damages (with and without the Waffle) represented mitigated flood damages (benefits). Benefits were computed and discounted annually over the 50-year period. Likewise, costs were estimated and discounted annually over the study period. Results from the analysis were expressed as the present value of net benefits (costs subtracted from benefits).

The analysis used several scenarios that reflected different expectations in Waffle size, cost, water storage capacity, and future population. Waffle size was divided into three acreage estimates (maximum, moderate, and minimum) each for a full-scale and half-scale Waffle. Further, two water storage assumptions (conservative and moderate) were provided for each scale. Costs were based on a baseline scenario, with several economic factors adjusted higher (pessimistic scenario) and lower (optimistic scenario) to provide a plausible range of expenses. Three sets of future FSDFs were generated for Fargo/Moorhead, Breckenridge, Wahpeton, Grand Forks/East Grand Forks, and Drayton based on baseline, optimistic, and pessimistic population forecasts. A host of scenarios was used largely due to the uncertainty pertaining to Waffle size and water storage capacity, knowledge gaps on the economic understanding of various operational aspects of the Waffle, and the inherent difficulties in projecting potential flood damages in study communities over a 50-year period. The combination of those situations produced 108 separate estimates of the net benefits of the Waffle.

Net benefits were positive in 106 of the 108 scenarios evaluated. The magnitude of net benefits over the 50-year period were substantial: 85 percent of the scenarios evaluated resulted in over $300 million in net benefits and nearly half of the combinations had net benefits in excess of $500 million. The results from two alternative analyses showed that the Waffle produced substantial net benefits when only used for relatively large floods (greater than 100-year events) and also revealed that the Waffle is not economically sensitive to the inclusion or absence of high-frequency flood damages from Fargo/Moorhead.

Overall, the economic feasibility of the Waffle, given the limited scope of benefits included in the study, was almost entirely determined by mitigated flood damages from Fargo/Moorhead. Without mitigated flood damages from Fargo/Moorhead, results from this study suggest the Waffle would only be economically under ideal conditions (11 of 108 possibilities) if implemented on a basin wide scale. Recent improvements and additions to structural flood protection in Wahpeton/Breckenridge and Grand Forks/East Grand Forks eliminate the potential to mitigate flood damages from all but the largest flood events. The relatively small pool of benefits produced by the Waffle in Wahpeton/Breckenridge and Grand Forks/East Grand Forks was insufficient to influence the economic feasibility of the Waffle under most conditions examined.

Observations from study results indicate that landowner payments (i.e., both retainer and water storage payments) had the most influence on Waffle costs. While payment acreage and payment rates greatly influenced expected costs, those cost factors did not affect economic feasibility. The economic feasibility of the Waffle also did not appear to be sensitive to the range of values used for future population in the study communities or water storage capacities. Again, while those factors had substantial effects on the level of gross benefits, conclusions on the economic feasibility of the Waffle were not influenced. The differences in net benefits between the full-scale and half-scale Waffle were greatest in the higher acreage scenarios, and diminishing net returns between the two Waffle scales suggest further analysis would be needed to determine an economically optimal scale for the Waffle. However, given current information, uncertainty on payment acreage and landowner enrollment makes estimating optimal Waffle size problematic.

Research over the past several years at the Energy & Environmental Research Center has demonstrated the technical feasibility of using a Waffle-based flood mitigation strategy in the Red River Basin. Even with several limitations in the scope of benefits and a lack of knowledge pertaining to some cost aspects of the Waffle, this analysis showed substantial potential for positive net benefits from using the Waffle to mitigate flood damages in the Basin. Questions remain regarding the financial feasibility of the Waffle, and many operational aspects and cost-related factors associated with the Waffle also remain unanswered. The positive results from this study suggest that dedicating additional resources to solving or answering many of the remaining issues with the Waffle would be justified. Perhaps additional resources could be used to implement a pilot version of the Waffle, albeit at a watershed or township level, to more fully understand the operational characteristics of the Waffle and provide the groundwork for more widespread implementation.

Benefit-Cost Analysis of the Waffle®: Initial Assessment

Dean A. Bangsund, Eric A. DeVuyst, and F. Larry Leistritz*

INTRODUCTION

The Red River of the North has a long history of flooding. Anecdotal evidence suggests substantial floods occurred in the late 1700s prior to widespread settlement in the region. The earliest recorded major flood in the Red River Basin was in 1826, and remains the largest on record for most of the basin (International Joint Commission 1997). Since 1826, the basin has experienced a number of large floods. Some of the most notable floods were in 1852, 1861, 1897, 1950, 1966, 1969, 1975, 1978, 1979, 1989, 1996, 1997, and 2006 (International Joint Commission 1997, Bolles et al. 2004). The flood of 1997 was among one of the worst on record for many locations within the basin, and revealed that existing flood protection measures were inadequate to prevent widespread damage.

The physical characteristics of the Red River Basin make the region susceptible to widespread spring flooding. One of the overriding characteristics is that nearly all of the basin is remarkably flat. From Wahpeton, ND to Lake Winnepig, Manitoba, Canada, the elevation changes about 233 feet over a distance of about 545 river miles (International Joint Commission 1997). The slope of the basin averages about 0.5 foot per mile, but varies from 0.2 feet per mile in the northern valley to about 1.3 feet per mile in the southern valley. The gentle gradient results in slow river flows that produce limited drainage capacity.

Additional problems within the region stem from a shallow river channel, combined with flat surrounding topography, which allows water to easily overflow river banks and quickly inundate surrounding lands. High clay content in the soils of the region provide limited water absorption and contribute to flooding (International Joint Commission 2000). Further, unlike many major river systems in the U.S., spring melt and runoff first occur in the headwaters. The Red River drains northward, so water flow can be slowed or stopped by frozen regions in the northern portions of the basin. This effect is often compounded by snow melt and runoff that continues to proceed northward with the flow of excess water from southern regions in the basin. These conditions can produce enormous potential for flooding (U.S. Army Corps of Engineers 1998, 2000a).

Other factors contributing to flood damages in the basin include drainage of natural wetlands, agricultural drainage on crop land, and the proximity of settlements in or near flood plains. Also contributing to flooding is the constriction of river channels from dikes and levees that exist near and around the major communities in the basin (U.S. Army Corps of Engineers 1998). In essence, the Red River basin is prone to flooding due to a host of natural

---

*Research scientist, associate professor, and professor, respectively, Department of Agribusiness and Applied Economics, North Dakota State University, Fargo.

features, and the social and economic effects of periodic flooding are accentuated due to manmade contributing factors.

Due to the frequent flooding and physical characteristics of the basin, numerous structural and nonstructural approaches have been considered to help mitigate flood damages. The primary structural flood mitigating strategies for spring floods have included dikes/levees, both permanent and temporary, and flood-water diversions or channels. Over the course of the past century, social, environmental, and economic criteria have been acceptable for creating dikes, levees, and diversions (International Joint Commission 1997). Despite the use of levees and diversions within the basin, spring flooding continues to cause damage and concern among the region's inhabitants.

Other measures, such as small- and large-scale dams and wetland restoration also have been considered. Currently, the perception is that an insufficient number of small- and large-scale dams would meet economic and environmental acceptance, and as such, the use of reservoirs would not provide substantial flood protection in the region (International Joint Commission 2000). The use of reservoirs would attenuate floods only if they were part of a broader strategy and combined with other measures (International Joint Commission 2000). Wetland restoration has been considered as a potential flood mitigation strategy, but it also has been deemed insufficient by itself to influence widespread flooding in the basin (International Joint Commission 2000, Shultz and Leitch 2003). Generally, within the greater Red River Basin, dams, wetland restoration, and other measures are not sufficient by themselves to make meaningful reductions in flood damages, and are not economical for widespread implementation to reduce flood damages.

Another option to mitigating flood damages in the Red River Basin is the concept of using hundreds or thousands of 'micro-basin' storage areas comprised of roads and adjacent lands throughout the region. The micro-basin concept would utilize roads and other existing structures to act as temporary barriers to contain snow melt and flood runoff on adjacent lands. Flood water would be managed through culvert modifications to temporarily store water on those lands. The goal of using micro-basin storage would be to contain a sufficient volume of water over a reasonable period in the spring to lower the flood crest heights on streams and rivers throughout the basin. Water contained in the micro-basins would be gradually released after the threat of flooding had subsided. The use of roads and adjacent lands within the basin to temporarily hold water during periods of spring flooding also has been the referred to as 'waffle storage' (International Joint Commission 2000).

In 2002, the Energy & Environmental Research Center at the University of North Dakota began investigating the feasibility of implementing a Waffle-based flood mitigation strategy for the Red River Basin (Bolles et al. 2004). The overall goal of the Waffle would be to provide additional flood protection to complement existing structural and non-structural flood mitigation strategies in the basin. Since the start of the project in 2002, most of the research effort has focused on hydrologic and hydraulic issues associated with spring-time floods. Initial results suggest a Waffle-based approach to flood control in the Red River Basin is technically feasible and could provide a substantial increase to existing flood protection measures in the region (Bolles et al. 2004).

While a Waffle-based flood mitigation strategy appears to be technically feasible in the Red River Basin (Bolles et al. 2004), the issue of economic feasibility has yet to be addressed. Insights on the economic feasibility of the Waffle will enable researchers, policy makers, civic planners, and other interested individuals to make important decisions on how to proceed with further research and/or implementation of the Waffle. If the Waffle is shown to not be cost-effective, further evaluation of the Waffle might not be appropriate; however, if the Waffle is shown to be cost-effective, justification would exist to devote additional resources towards evaluating remaining issues (e.g., legal, strategic, and operational questions, and address any remaining hydrologic and hydraulic modeling concerns). Further, insights on the economic feasibility of the Waffle might influence the development of other flood mitigating efforts in the event that the Waffle is unlikely to be implemented as a flood mitigation strategy. The purpose of this report is to provide a first assessment of the cost-effectiveness of the Waffle and provide insights into the economic feasibility of using the Waffle to mitigate flood damages in the Red River Basin.

OBJECTIVES

The purpose of this report is to evaluate the economic feasibility of the Waffle using a benefit-cost analysis. Specific objectives include:

1) estimate the costs of maintaining and operating the Waffle,

2) estimate the mitigated flood damages (benefits) from the Waffle, and

3) estimate net benefits of the Waffle over a reasonable range of physical and economic values.

METHODOLOGY

The overall method used to evaluate the economic feasibility of the Waffle was a net present value analysis. Present value analyses attempt to track the costs and benefits of a project or activity over a specific period. Typically, projects or activities, such as the Waffle, are evaluated over extended periods (i.e., 25 to 50 years). Given the time frames involved, a variety of estimation techniques are usually required to project costs and benefits over the life of the project/activity. In addition, costs and benefits are often discounted to account for the influences of time on economic values. The following sections describe both data and techniques used to project future costs and benefits.

Data

Data for this study came from a number of sources. Descriptions and use of data are contained in the following sections, while the presentation of most data is contained in appendices.

Acreage

Two primary issues pertain to acreage of land associated with the Waffle. Land throughout the Red River Basin was evaluated for the potential to temporarily store water based on criteria developed by the Energy & Environmental Research Center (EERC) at the University of North Dakota (Bolles et al. 2004). Land associated with the Waffle can be divided into *flooded acreage* and *payment acreage*. *Flooded acreage* represents the amount, location, and type of land used for temporary water storage, and represents only the surface acreage of land used to intentionally retain water through a series of culvert control devices. However, the economic analysis needed to distinguish between the amount of land actually flooded and the amount of acres that would require some form of compensation. *Payment acreage* represents both estimates of the flooded acreage and estimates of additional acreage affected by temporary water storage. Those additional acres would be inaccessible for farming or other uses due to lost access (e.g., surrounding water prevents or blocks access to non-flooded land).

Due to varying elevations within any given section[1] of land throughout the Red River Basin, the acreage affected by temporary water storage is going to be greater than the acreage of land that temporarily holds flood water (Figure 1). The intentional flooding of land in most situations can affect access and/or use of adjacent or nearby land within any given section. The extent of additional land affected by intentional flooding within any particular section will vary based on a number of factors, but one of the key elements is the amount of relief or change in elevation within and around that section. Land suitable for use in the

---

[1] A section of land is typically considered to be one mile by one mile and is approximately 640 acres.

Waffle (i.e., flooded acreage) was divided into three relief categories[2], and the basin-wide potential for additional acreage affected by the Waffle varies for each of the relief categories (Figure 1). In situations where little elevation change occurs within a section (i.e., relief category 0-2), the amount of additional land (i.e., non-flooded land) affected by temporary flooding can be relatively low. For moderate changes in elevation within a section (i.e., relief category 2-4), a greater potential exists for additional land to be affected by temporary flooding. In situations where greater overall changes in elevation occur (relief category 4-11), the amount of land affected by temporary flooding can be quite variable. Flooding within the section can be localized to one end of the section, concentrated on the periphery of the land tract, or represent a combination of situations where substantial acreage is affected by relatively minor amounts of flooded acreage (Figure 1).

Bolles et al. (2004) documented the process of how land was deemed suitable for use in the Waffle. Land suitable for temporary water storage in the Red River Basin is available in 43 counties in North Dakota, Minnesota, and South Dakota. The surface use or physical characteristics of the land were described by thirteen different land categories (Table 1). Land within each county and classification was further separated by three relief categories (i.e., a measure of the relative change in elevation within a given land tract). Thus, land suitable for the Waffle was delineated by land classification, county, and relief category. After determining the amount of land suitable for use in the Waffle, a series of analyses were conducted, based on elevation and topographical data, to estimate the amount of payment acreage associated with the Waffle (Kurz et al. 2007).

Some adjustments to the payment acreage data were performed for the economic analysis. Initially, cropland and pasture were reported by the EERC as a single land use category. To more accurately estimate the potential payments required for the two land types, separate estimates of the acreage for cropland and pasture were generated. County-level data on the total acreage of cropland and pasture were obtained from National Agricultural Statistics Service (2004). A county-wide ratio of cropland to pasture was used with Waffle data to create separate estimates of the amount of payment acreage for cropland and pasture. The analysis assumed that the payment acreage of cropland and pasture in the Waffle, which was initially combined in one land use category, would be representative of the county-wide ratio of cropland and pasture acreage obtained from the National Agricultural Statistics Service (2004).

---

[2] The three relief categories were designated as 0-2, 2-4, and 4-11. The relief category 0-2 represents tracts of land with relatively small amounts of elevation change within those tracts. The relief category 2-4 represents tracts of land with greater relative amounts of elevation change within those tracts. The relief category 4-11 represents tracts of land with relatively large changes in elevation within those tracts.

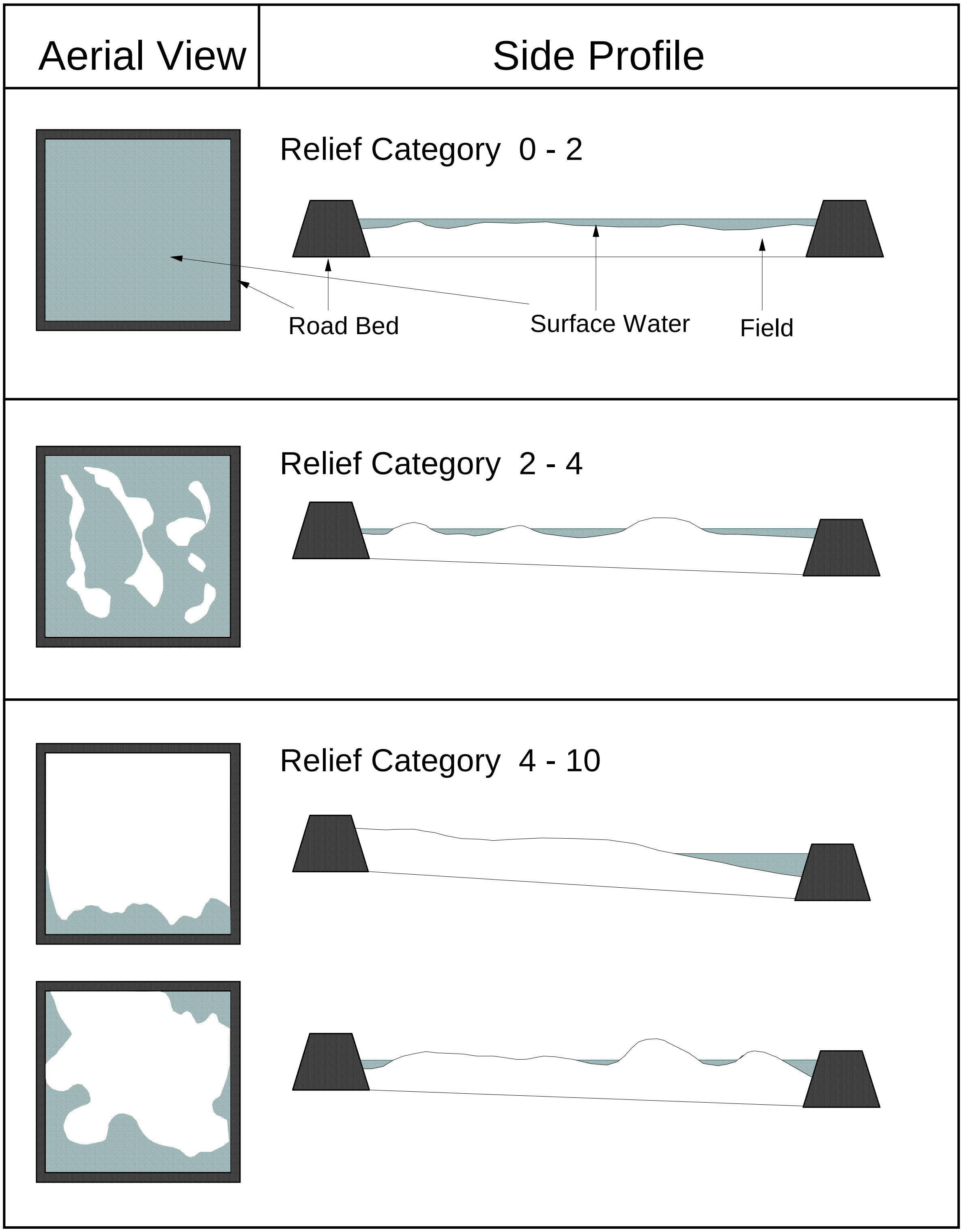


Figure 1. Conceptual Relationship between Land Relief, Flooded Acreage, and Payment Acreage for Land Enrolled in the Waffle.

Table 1. Classification of Land in the Waffle

Land Use Categories for Economic Analysis	Land Use Categories for Modeling Water Storage	Share of Land in the Waffle
Cropland	Cropland and Pasture	86%
Pasture	Cropland and Pasture Herbaceous Rangeland Mixed Rangeland	4%
Other Land	Deciduous Forest Evergreen Forest Lakes Forested Wetland Nonforested Wetland Strip Mines, Quarries, Gravel Pits Transitional Areas- - Barren Ground Transportation, Communication, Utilities Industrial	10%

Source: Energy & Environmental Research Center (2007).

For purposes of estimating landowner compensation for participation in the Waffle, the economic analysis also assumed that pasture and rangeland could be combined into one land use category. Data on payment acreage for land in the Waffle included two additional rangeland categories (i.e., Herbaceous Rangeland and Mixed Rangeland) (Table 1). Estimates of pasture acreage and estimates of acreage in herbaceous and mixed rangeland were combined into one land use category in each county. Despite the different land use designations, from an economic perspective, rental rates for pasture and rangeland in the Red River Basin were assumed to be similar.

Time and resource constraints prevented the development of separate payment rates for all land use categories. For the economic analysis, remaining land use categories were combined into an ‘other’ land category (Table 1). Examples of the land use categories that were combined into the ‘other’ category include wetlands, forests, lakes, and developed areas.

Two scale options for the Waffle were considered. The full-scale and half-scale options were based on differing rates of utilization of land suitable for use in the Waffle, and do not refer to the geographic scope of the Waffle. The full-scale option assumes all land suitable for use in the Waffle is enrolled, while the half-scale option assumes half of the land suitable is enrolled. The Waffle was considered to be implemented basin wide (i.e., U.S. portion only), and the reduction in acreage in the half-scale scenario was distributed evenly across all suitable land. Three potential estimates of payment acreage were developed for each scale. These three acreage estimates were developed to account for the uncertainty associated with estimating actual acreage affected by water storage because of different estimation techniques and various sources of land elevation data (Kurz et al. 2007). As a result of having two scale options with three acreage estimates per scale, a total of six possible combinations of Waffle acreage were generated. For the full-scale option, total Waffle payment acreage basin wide ranged from 1.4 million acres for the maximum scenario to 405,000 acres for the minimum scenario. Total Waffle payment acreage basin wide for the half-scale option ranged from 709,000 acres for the maximum scenario to 204,000 acres for the minimum scenario. The greatest acreage was enrolled in Minnesota across all combinations (Table 2). Cropland composed the greatest percentage of land enrolled in the Waffle across all six combinations (Table 2). County level acreage estimates by land type, classification, and relief contour were placed in Appendix A.

Number of Sections of Land

Information on the number of sections of land in the Waffle was required to estimate the cost of culvert modifications. Unfortunately, the number of sections of land cannot be directly determined from payment acreage. In many cases, the acreage of land within any section used to temporarily store water is considerably less than the 640 acres in a section. The EERC provided the number of sections of land by county and relief category for each land use classification (Appendix A).

Culvert Modifications

The fundamental concept associated with the Waffle is the ability to temporarily store water in micro-basins created by the network of roads and adjacent fields. Temporary water storage can only be accomplished if the Waffle can control the amount of water and the length of time water is stored. The Waffle can accomplish those goals by installing control devices on culverts in the sections of land enrolled in the Waffle. These devices are designed to hold back water at a pre-determined height, but allow additional water to naturally flow over the pipes and through the culverts. When the threat of flooding has passed, stored water would be gradually released so as to not contribute to additional flooding.

The collection and analysis of data on the number of culverts, size of culverts, and distribution of culverts throughout the entire Red River Basin was beyond the scope of this study. However, the EERC was able to use data previously collected for their hydrologic and hydraulic modeling to generate estimates of the number and size of control devices needed, based on relief category, in three watersheds in the Red River Basin. The EERC also was able to estimate the useful life of the control devices based on anticipated operating conditions (e.g., water pH, frequency of use). Based on the above factors, the EERC produced estimates of the per-section infrastructure costs of modifying existing culverts and the anticipated installation expenses for the control devices (Appendix B). Based on data in

2005, culvert control devices ranged from about $3,600 per section for relief category 4 - 10 to $11,600 per section for relief category 0 - 2. Installation costs in 2005 were estimated to range from $800 per section for relief category 4 - 10 to $1,200 per section for relief category 0 - 2.

Table 2. Estimates of Payment Acreage by Waffle Size

	Full-scale		Half-scale	
Category	Minimum	Maximum	Minimum	Maximum
<u>State</u>				
North Dakota	191,840	628,320	96,256	315,040
Minnesota	210,016	776,800	105,888	388,960
South Dakota	3,456	9,440	1,728	4,800
Total	405,312	1,414,560	203,872	708,800
<u>Land Type and Relief Contour</u>				
Cropland				
0 - 2	140,431	421,293	72,525	217,576
2 - 4	109,914	549,572	53,722	268,611
4 - 10	100,183	250,457	49,980	124,949
Total	350,528	1,221,323	176,227	611,136
Pasture				
0 - 2	4,529	13,587	2,355	7,064
2 - 4	4,329	21,628	2,150	10,749
4 - 10	8,361	20,903	4,484	11,211
Total	17,216	56,117	8,989	29,024
Other Land				
0 - 2	19,840	59,520	9,440	28,320
2 - 4	13,312	66,560	6,912	34,560
4 - 10	4,416	11,040	2,304	5,760
Total	37,568	137,120	18,656	68,640

Note: A moderate acreage scenario representing an approximate average between the minimum and maximum acreage was omitted from the table.

The cost data provided by the EERC were used with data on the number of sections to produce estimates of the basin-wide costs of purchasing and installing the culvert control devices. A lack of data and resources prevented the study from using separate estimates for each watershed in the Red River Basin or separate estimates for smaller geographic units (e.g., township, county). Instead, the per-section infrastructure and installation costs for the Red Lake Watershed were used to produce estimates for the entire basin (Appendix B). The characteristics of the number, size, and distribution of culverts in the Red Lake Watershed were considered sufficient to project costs for the entire Red River Basin. Since costs were based on 2005 data, minor adjustments to the infrastructure and installation expenses were included in cost projections.

Landowner Compensation

A premise early in the evaluation of the technical and economic feasibility of the Waffle was that landowners who enrolled land in the Waffle would receive some level of financial compensation. Specifics on the level of compensation needed or required have not been fully explored; however, the premise that financial compensation will be required for landowners to participate in the Waffle is generally accepted (Bolles et al. 2004).

This study was not designed to address a number of questions pertaining to landowner compensation rates, such as the level of compensation required to secure landowner cooperation, the upper level of compensation capable of being paid by the Waffle, or the contract structure or payment structure most favorable to landowners. These and other financial compensation issues are well beyond the scope of this study. It is likely that insights on amount of financial compensation needed to entice most landowners and producers to enroll land in the Waffle will not be fully understood until many of the details on planting delays and other potential physical effects on crop production stemming from temporary water storage can be determined. Similarly, issues on contract or payment structure will remain unresolved until it is known how participation in the Waffle may affect other income sources (e.g., crop insurance payments, farm program provisions). Instead, the approach used in this study was to evaluate the cost-effectiveness of the Waffle over a plausible range of financial compensation levels.

In order to evaluate a range of payment levels consistent with the economic value of land enrolled in the Waffle, the analysis tied financial compensation rates to the level of cash rents for non-irrigated cropland and pasture. From an agricultural perspective, cash rents are a market-based level of compensation, negotiated between a landowner and an agricultural producer in the form of a cash payment, that secures the right of a individual(s) to produce or raise a crop on leased land. This approach provides sufficient flexibility to evaluate the overall effects of different payment rates on the cost-effectiveness of the Waffle and still tie compensation rates to general land productivity without requiring specific information on landowner preferences or requirements.

County-level cash rent data for cropland and pasture/rangeland in North Dakota and South Dakota were obtained from the National Agricultural Statistics Service (2005a, 2005b) while cash rent data for Minnesota were obtained from Hachfeld et al. (2005) (Appendix C). Estimates of future levels of cash rent were based on the index of cash rent paid by farmers in the U.S. (U.S. Department of Agriculture 1997, 2005). The cash rent index was adjusted for inflation using the Gross Domestic Product-Implicit Price Deflator (U.S. Department of Commerce 2006). The long-term trend in real (i.e., inflation adjusted) cash rents was used to project future levels of cash rent in the Red River Basin.

The level of cash rents vary throughout each county based on a variety of factors. Some of the most prevalent factors include land productivity, crops raised, and individual landowner preferences and rental arrangements. For example, cash rents for land used to raise sugarbeets are usually higher than for land used to raise small grains. Also, cash rents for land outside of the Red River Valley are generally lower than cash rents for land in the Valley. While these and other differences can influence the level of cash rents, projected values for county average cash rents were used for all land within a county enrolled in the Waffle. Data were not available to differentiate Waffle acreage within a county for purposes of adjusting payment levels associated with potential variations in the level of cash rent. All payments for land in each county were tied to a single level (i.e., average value) for cash rent in that county. Using an average cash rent value for all Waffle acreage in a county results in compensation rates being higher in some situations and lower in other situations than if payment levels were more closely tied to local conditions.

While future cash rent values were projected based on a long-term trend in real cash rents, several factors can influence the level of expected cash rents in the future. Examples of those factors may include a change in the mix of crops grown in the Red River Valley and market effects of shifts in domestic demand and supply for agricultural commodities. Examples of both factors are currently occurring as a result of recent market influences associated with ethanol and bio-fuels. The increased demand for corn has resulted in higher corn prices, increased acreage allocated to corn production, and increases in cash rents. By contrast, if high value row-crops, such as sugarbeets and potatoes, disappear from the Valley and are not replaced with other high value row-crops, cash rents could actually decrease (in real terms).

Flood-stage Damage Functions

The economic analysis needed to estimate the mitigated flood damages (i.e., benefits) that are likely to result from implementing the Waffle. In order to estimate mitigated flood damages, it was critical to determine the likely amount of flood damages over a reasonable range of flood crest heights for specific points along key tributaries and rivers in the basin.

The key economic component for developing estimates of the potential mitigated flood damages (benefits from the Waffle) in this study was the flood-stage damage functions developed by the U.S. Army Corps of Engineers (USACE). The flood-stage damage functions estimate flood damages that are likely to occur in a community at various crest heights for major rivers/tributaries in the region. Conceptually, within the benefit-cost framework, the benefits of the Waffle represent the difference in flood damages that can be expected to occur with and without the Waffle. Flood-stage damage functions provide the basic information needed to estimate the mitigated flood damages associated with the Waffle.

Flood-stage damage functions (FSDFs) were obtained for Fargo-Moorhead, Grand Forks-East Grand Forks, Wahpeton, Breckenridge, Grafton, Drayton, and Crookston (Table 3) (U.S. Army Corps of Engineers 1997, 1998, 2000a, 2000b, 2003, 2004, 2005). The FSDFs were based on data from different years. The years for which the FSDFs were developed ranged from 1995 for Crookston to 2004 for Fargo-Moorhead. While all functions contained estimated damages for residential and commercial property, the FSDF for some communities also contained additional damages and costs for relocation, public infrastructure, vehicle damages, and emergency response expenses (Table 3).

Table 3. Flood-stage Damage Functions, Selected Cities, North Dakota and Minnesota

Location	Damages Included in Functions	Base Data for Functions
Fargo/Moorhead/ Oakport Township, MN	Residential property, commercial property, public infrastructure, relocation costs, vehicle damages, emergency response costs	2004
Grand Forks/East Grand Forks	Residential property, commercial property, public infrastructure	1997
Wahpeton	Residential property, commercial property	1999
Breckenridge	Residential property, commercial property	1999
Grafton	Residential property, commercial property, public infrastructure, relocation costs, vehicle damages, emergency response costs	2002
Drayton	Residential property, commercial property, public infrastructure, relocation costs, vehicle damages, emergency response costs	2003
Crookston	Residential property, commercial property	1995

The FSDF provide the general relationship between flood severity and level of flood damages. For all communities, except Fargo-Moorhead, the FSDF needed to be adjusted to reflect current conditions. The level of damages estimated in the functions are subject to changes in the level of flood protection in the community and changes in the aggregate value of property at risk from flooding. Discussions with personnel from the USACE indicated that the FSDFs were based on existing permanent flood protection measures in each community at the time the functions were estimated (U.S. Army Corps of Engineers 2006). Alternatively, the level of flood protection within most of the communities has changed due to the addition of permanent dikes/levees, relocation of residential and/or commercial properties, the addition of diversions or floodways, and/or changes in the protection provided by increasing the height of existing levees/dikes. In addition, the damages projected in the FSDFs were based on permanent flood protections that met with approval from the USACE within each community, and do not include adjustments to damages provided by temporary flood protection measures (e.g., earthen levees constructed during severe floods, adding fill to increase the height of existing permanent levees). Finally, the damages in the functions do not reflect the new, or in some cases, expected future flood protection levels once ongoing flood protection projects are finished. For example, the FSDF for Grand Forks-East Grand Forks was estimated based on data from 1998, and the relationship between flood severity and expected flood damages does not account for the changes in local flood protection measures recently implemented in the two cities (i.e., increased scope and height of levees/dikes and residential property relocations). Similarly, recent improvements in the protection levels provided by higher levees/dikes in Wahpeton and Breckenridge and the completion of the diversion near Breckenridge were not included in the FSDF for those cities.

Since the FSDFs were not reflective of the expected future level of flood protection measures in some cities, damage estimates for some flood crest elevations within the FSDFs were eliminated (i.e., damages were put to zero). In the case of Grand Forks/East Grand Forks, Wahpeton, and Breckenridge, current flood protection projects are expected to eliminate damages according to the USACE for defined areas of the cities below a certain crest height. The elimination of damages in Grand Forks/East Grand Forks, Wahpeton, and Breckenridge are treated differently than expected damages in Fargo/Moorhead. In the case of Grand Forks/East Grand Forks, Wahpeton, and Breckenridge, the elimination of flood damages comes from USACE approved flood protection measures so all estimated damages for flood crest heights below the capacity of the flood protections can be expected to be eliminated. However, the USACE does not recognize the ability of temporary dikes and levees in Fargo and Moorhead to provide protection when creating the FSDF in those cities. Essentially, local flood fighting efforts are not credited with eliminating flood damages in Fargo/Moorhead. As a result, the FSDF indicates substantial damages due to floods of modest size while real world conditions indicate that the cities of Fargo/Moorhead, to date, have been very successful in preventing most damages using a variety of temporary flood fighting provisions in conjunction with permanent levees. Unfortunately, it is clearly beyond the scope of this study to estimate the difference between the amount of damages that are predicted within the FSDF and the amount of actual (i.e., out of pocket) losses incurred within the two communities for any-sized flood over the next 50 years.

The discrepancy between the estimates of damages in the USACE FSDFs and the actual value of flood damages in Fargo/Moorhead would require some revision of the definition of damages and/or some recognition of the ability of temporary dikes/levees to abate flood damages. Within the issue of the definition of expected flood damages is the cost of providing temporary dikes/levees and the non-monetary value of volunteer labor and donated materials used in sandbagging and other local flood fighting measures. A more comprehensive approach would be to more clearly define whether damages need to be actual or if they should be hypothetical in the absence of temporary dikes/levees and include some estimates of the costs, which should include non-monetary expenses, of temporary flood fighting measures. The USACE definition of damages was used to estimate the benefits of the Waffle, even though the damage estimates within the FSDF may not necessarily relate to real world conditions for all flood events.

Population Projections

Future values for the FSDFs were based on three possible population projections for each city. The population projections were based on data and reports developed for the Red River Valley Water Supply Project and on information from the Minnesota State Demographic Center (Minnesota State Demographic Center 2002, Bureau of Reclamation 2005, Northwest Economic Associates 2003). The three population projections included a main projection, a optimistic projection and a pessimistic projection. The implications for future population were different in most cities for each scenario. For example, the population for Fargo was expected to increase in each scenario, whereas, population for all but the largest communities decreased in the pessimistic scenario (Appendix C). The optimistic projection had an 18 percent increase in population over the base scenario. The pessimistic scenario had a 14 percent decrease in population over the base scenario. Total population in 2050 in the study communities for the main, optimistic, and pessimistic scenarios was 370,453, 437,240, and 318,341, respectively (Appendix C). Since the evaluation period for the Waffle was extended out to 2055, populations for the study communities in all projections were based on simple extrapolations to 2055 of population growth between 2045 and 2050 in each city.

Residential and Commercial Property Values

The nominal value of aggregate residential and commercial property values in each study community was collected to provide data to adjust the FSDFs to current conditions (i.e., 2005) and provide input for projecting future values for the FSDFs. While the number of years of data available varied by community, information on aggregate residential and commercial values were obtained back to 1990 for most cities (Appendix C). In nearly all cases, information on nominal aggregate residential and commercial values were obtained from city and county governments. All residential and commercial property values were net of land (i.e., value of land was not included). The values used in this study only include residential structures covered by local property tax regulations, and may not contain items such as storage sheds, dog kennels, or other miscellaneous facilities/items.

Indices

Several indices were used to adjust nominal values to real (i.e., corrected for effects of inflation) values, as well as provide information for projecting future FSDF values between 2006 through 2055.

Office of Federal Housing Enterprise Oversight

The Office of Federal Housing Enterprise Oversight (OFHEO) is an independent entity within the U.S. Department of Housing and Urban Development that has oversight responsibilities for the Federal National Mortgage Association (Fannie Mae) and Federal Home Loan Mortgage Corporation (Freddie Mac). The OFHEO also maintains a housing price index that tracks the movement of single-family house prices throughout the United States and in specific geographic areas (Office of Federal Housing Enterprise Oversight 2006). Separate OFHEO indices were obtained for Fargo-Moorhead, Grand Forks-East Grand Forks, North Dakota, and Minnesota (Appendix C). The OFHEO housing price index is reported quarterly in nominal dollars. The OFHEO index was adjusted by the Consumer Price Index for Housing to reflect a real housing price index (i.e., inflation adjusted).

Consumer Price Index

The Consumer Price Index (CPI) is a measure of the change in prices over time for various bundles of goods and services purchased by consumers in the United States. The CPI is often used to measure inflation in the United States economy. The Consumer Price Index for Housing was used to adjust the OFHEO housing price index to reflect real dollars (Appendix C).

National Council of Real Estate Investment Fiduciaries

The National Council of Real Estate Investment Fiduciaries (NCREIF) tracks the capital and income returns from a variety of commercial property acquired in the private market for investment purposes. Since a commercial real estate index was not available from public sources, data from the NCREIF property index on quarterly capital appreciation were combined with the Gross Domestic Product-Implicit Price Deflator to create a real commercial property index.

U.S. Bureau of Economic Analysis

The U.S. Bureau of Economic Analysis, U.S. Department of Commerce, tracks the value of all goods and services produced by labor and property in the U.S. This value is reported as the gross domestic product, which is used to measure the size and growth of an economy. The U.S. Bureau of Economic Analysis also produces a number of indices designed to track the changes in prices within an economy. One of those indices is the Gross Domestic Product-Implicit Price Deflator (GDP-IPD) which is not limited to price changes felt by consumers. The GDP-IPD was used to adjust some indices from nominal dollars to real dollars.

U.S. Department of Agriculture

The U.S. Department of Agriculture (USDA) provides a nominal index for cash rents paid on farmland in the U.S. (U.S. Department of Agriculture 1997, 2005). The nominal index was adjusted using the GDP-IPD to produce a real cash rent index. The change or trend in the real cash rent index was then used to project the rate of change in future cash rents, which was part of the model used to estimate future costs of the Waffle.

Methods

The economic framework for analyzing the Waffle is a net present value analysis. In its simplest form the sum of the present value of costs is subtracted from the sum of the present value of benefits to assess the economic advisability of the Waffle. A 50-year time horizon was used, which is consistent with the USACE time horizon for similar evaluations and coincides with the estimated useful life of culverts and other structural modifications needed to implement the Waffle. A real discount rate, *d*, of 5 percent is used. The net present value of the Waffle is computed as:

$$\textbf{(1)} \qquad NPV = \sum_{t=2006}^{2055} (E[B_t] - C_t) \times (1 + d)^{-(t-2005)}$$

where $E[B_t]$ are expected benefits and C_t are costs in year *t*.

Benefits

Benefits accruing from the Waffle include mitigated flood damages to residential, commercial, and public property, prevented disruptions to economic activity, and various environmental benefits, such as improved water quality, reduced soil erosion, and subsoil moisture and groundwater recharge. Unfortunately, quantitative measures of these benefits were only estimated for flood damages to buildings and infrastructure in the largest municipal areas within the U.S. portion of the Red River Basin. Estimates of the environmental benefits of the Waffle would require substantially more resources than were available to conduct this study. Subsequently, only mitigated flood damages are considered as economic benefits. This limitation in the breath of benefits means the economic feasibility of the Waffle is narrowly based only on its flood mitigation effects. Within that context, the scope of this study is further limited to only include mitigated flood damages for a limited number of communities in the Basin. These two limitations in scope suggest that the results provided in this report be viewed as highly conservative estimates of economic viability of the Waffle.[3]

A flood-stage damage function relates flood crest height, measured in elevation above mean sea level (msl) or some reference flood height, to expected property damages. Crest heights at a given point on a river are tied to annual flood frequencies. The annual flood frequency represents the probability or likelihood of a crest height reaching a given elevation. For example, a 100-year flood event has the probability of occurrence of 0.01 (1 chance in 100 years). The FSDFs provide estimates of damages for numerous crest heights at the given location, and those crest heights are often expressed in 1-foot increments above and below a reference flood elevation. Data for the FSDF for Fargo/Moorhead/Oakport Township are presented as an example (Table 4). Appendix D contains data on flood frequencies and flood elevations used in the FSDFs for other cities.

Despite listing flood damages for 1-foot increments in crest elevations, not all crest elevations were provided with a flood frequency. Using reported elevations and associated flood frequencies as reference values, linear interpolation and extrapolation were employed to estimate the missing frequencies (Table 4). The result is that each elevation within the FSDF has an annual probability of occurrence.

For each municipal area, USACE reports only a few elevations with frequencies. For example, the FSDF reported in Table 4 shows elevations for the 2-, 5-, 10-, 20-, 50-, 100-, 200-, and 500-year events. Frequencies are not reported for each elevation. The impacts of the Waffle, however, are not likely to fall exactly on these frequencies. For example, a 100-year flood event pre-Waffle is not likely to become exactly a 50-year (or 20-year) event post-Waffle. Linear interpolation and extrapolation techniques were used to approximate frequencies of various elevations (Table 4). The resulting FSDF can then be used to evaluate flood damages for nearly all flood events. Similar adjustments to the FSDFs were performed for the other cities (Appendix D).

---

[3] Essentially, all of the costs of operating the Waffle are included in this study, but only a subset of the actual benefits are estimated and included in the final analysis. Costs are not likely to change with the addition of environmental benefits to the analysis.

Table 4. Flood-stage Damage Function, Fargo, Moorhead, and Oakport Township, 2005

U.S. Army Corps of Engineers Data			Flood-Stage Damage Function		
Recurrence Interval	Flood Frequency	Crest Height (msl)	Crest Height (msl)	Flood Damages (000s $)	Interpolated/ Extrapolated Flood Frequency
2-year	0.5	881.34			
5-year	0.2	888.92			
10-year	0.1	891.66			
			894	0	0.0602
20-year	0.05	894.6	895	4,401	0.04689
			896	7,540	0.03912
			897	13,686	0.03135
			898	39,387	0.02358
50-year	0.02	898.46	899	107,795	0.01789
			900	277,569	0.01398
100-year	0.01	901.02	901	543,441	0.01008
			902	1,173,942	0.0075
200-year	0.005	902.98	903	1,765,180	0.00497
			904	2,396,937	0.00349
500-year	0.002	905	905	3,018,172	0.002
			906	3,662,200	0.00051

Source: U.S. Army Corps of Engineers (2005).

To compute expected damages, the FSDF is integrated from the lower end of damages distribution to the maximum specified flood crest, H. Mathematically, a FSDF is a probability density function. As a FSDF is given as set of discrete points and flood frequencies, it is necessary to fit a piece-wise linear function through the points to approximate the underlying probability density function. In Figure 2, the points of the FSDF are represented with an “+” and linear segments connect each of the points. An integral in used to compute expected damages as follows:

(2)

$$E[D] = \int_0^H D\cdot f(D)dD$$

where *E[D]* is expected flood damage and *f(D)* is the piece-wise linear flood stage probability density function. Marginal damages beyond *H* are presumed zero as all property has been destroyed at a crest height of *H* and beyond.

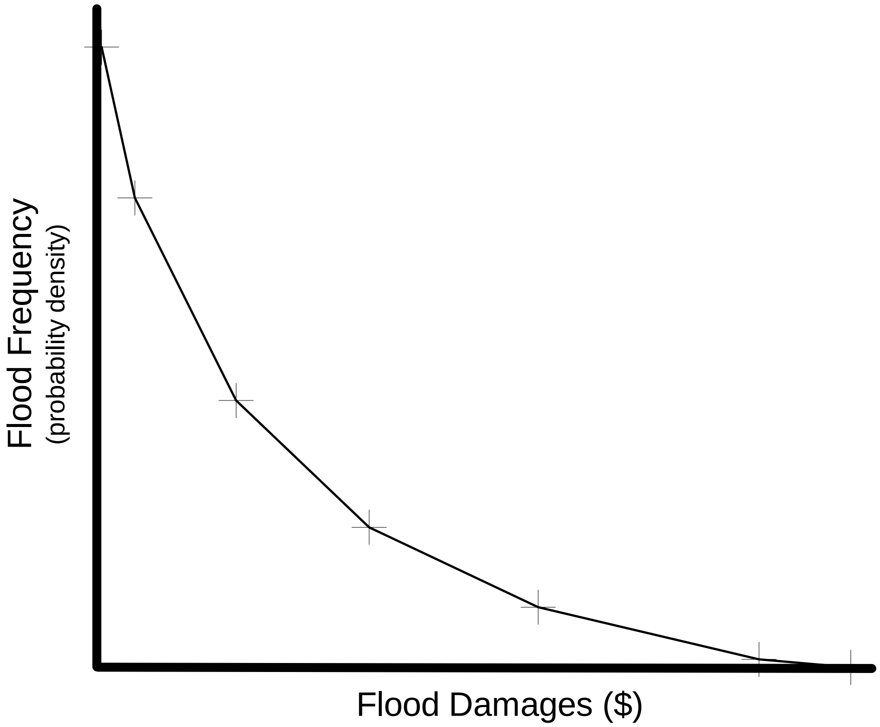


Figure 2. Conceptual Diagram of Flood Frequency and Flood Damages within a Piece-wise Linear Function.

The analysis used in this study needed to estimate benefits of the Waffle over a 50-year period. One approach would be to estimate the mitigated flood damages (i.e., damages with and without the Waffle) for a single year, and then project that year's benefits over a 50-year period. Therefore, mitigated flood damages would come from a single FSDF for each city, with the FSDF for that city being tied to economic conditions present at the time the function was developed (e.g., 2004 for Fargo/Moorhead). The USACE has primarily used the above approach in forecasting project benefits in their assessments of the economic feasibility of structural flood protection measures in communities in the Red River Basin (U.S. Army Corps of Engineers 1997, 1998, 2000a, 2000b).

A key problem with the USACE approach is that over a 50-year period the aggregate value of local property at risk of flooding is likely to change. If local conditions change, then expected flood damages represented in the FSDF also are likely to change. However, the number of physical, social, and economic factors affecting property at risk from flooding is likely to be numerous, and forecasting those values, and their effect on estimated flood damages, is beyond the scope of this study. This study developed an approach that allowed FSDFs to change over time with growth (or decline) in population and with changes in real (inflation adjusted) property values, assuming all other factors held constant. The end result is an annual series of FSDFs for each city from 2006 through 2055. An integration was performed for each annual function for each city, thereby allowing potential benefits from the Waffle to change over time as cities change population and as property values change.

The USACE developed FSDFs for Grand Forks/East Grand Forks, Fargo/Moorhead, Breckenridge, Wahpeton, Drayton, Grafton, and Crookston over various years, ranging from 1995 to 2005 (see Table 3). So while the functions, regardless of date produced, provide the basic relationships between flood event size (i.e., river crest height) and expected flood damages, the FSDFs for most cities needed to be updated to account for recent changes in aggregate property values and the influences of new or improved structural flood mitigation projects. First, the flood-stage damage functions were updated to reflect 2004 conditions[4]. After values were changed to reflect 2004 conditions, annual functions from 2006 through 2055 were forecasted to reflect changes in population and property values. Finally, the influences of new or improved structural flood mitigation projects on the FSDFs were incorporated. The techniques used to make those adjustments and changes are discussed in the following sections.

Updating Residential Flood-stage Damage Functions

The aggregate value of residential, commercial, and public infrastructure properties at risk of flooding has changed since the FSDFs were developed. To adjust for these changes, data on the aggregate value of residential and commercial properties, net of land, from 1990 through 2004 were collected from city and county agencies (see Appendix C).

Two sources of change in the aggregate value of residential properties were considered. First, the aggregate value of existing residential structures at the time of the Corps' estimation of the FSDF (here after called report date) could have changed–probably appreciated in value. Second, the addition of residential structures built since the report date also would increase aggregate property values. The two components influencing the aggregate value of properties are represented as:

(3) $\Delta\text{Aggregate property value}_t = \Delta\text{existing property value}_t + \text{value from new construction}_t$.

For residential structures existing at the report date, a real index of housing values (hereafter called real housing index) was constructed using the Office of Federal Housing Enterprise Oversight (OFHEO) nominal housing index and the Consumer Price Index (CPI) for Housing. Separate housing value indices were available for Fargo-Moorhead and Grand Forks-East Grand Forks. State-level indices for MN and ND were used for the remaining

---

[4] At the time the study was initiated, data were only available through 2004. Funding and time constraints prevented the inclusion of more recent data.

cities in each respective state. The real housing index was applied to residential damages at each flood-event elevation (i.e., crest height) in the FSDFs, thereby providing an update to the FSDF to account for changes in the real value of existing structures as of 2004.

Updating the FSDFs also required adjusting for additional damages arising from residential structures built after the report date for each municipal area. For the cities of Moorhead, Grand Forks, and Wahpeton, nominal aggregate housing values were available for 1990 through 2004. For the remaining cities, missing data were estimated using linear interpolation/extrapolation or by correlation of values from a nearby city with a 15-year series of published aggregate housing values. Using the OHFEO Index of Housing Prices and the CPI for housing, aggregate housing values from the report date were adjusted to 2004 dollars. The real aggregate housing value from the report date (reflected in 2004 dollars) was compared to the aggregate housing value in 2004. The difference in the two values was assumed to be due to additional residential structures.

All residential structures (i.e., primarily homes) added since the report date (1997 or later for all but one city) were assumed to be constructed at or above the elevation that corresponds to the 100-year flood event for that city. This assumption means that the FSDFs do not include additional damages for new residential structures at elevations below the 100-year flood event. At and above the 100-year flood elevation, additional damages were incrementally added to each elevation in the FSDF based on the relationship of existing damage values (i.e., in 2004 dollars) to the real value of aggregate residential values from the report year. This approach assumes that not all new residential structures would be affected at the 100-year and higher elevations, instead an increasing percentage of the aggregate value of new residential property was added as crest heights increased above the 100-year elevation in the FSDFs. Essentially, the FSDFs were adjusted to reflect greater damage to new residential properties the more crest heights exceeded the 100-year flood elevation.

Updating Commercial Flood-stage Damage Functions

As with the residential FSDFs, two sources of change are considered in the damage functions. First, aggregate value (i.e., net of land) for existing commercial properties since the report date for each municipal area has changed–often depreciated. Second, new commercial structures have been built and renovations/improvements have been made to existing structures since the report date.

A real commercial property value index was applied to commercial damages at each flood-event elevation (i.e., crest height) in the FSDFs, thereby providing an update to the FSDF to account for changes in the real value of existing structures as of 2004. This adjustment accounts for change in potential damages due to change in the real value of pre-existing commercial properties.

Aggregate commercial property value from the report year was adjusted to reflect 2004 dollars and compared to the actual aggregate property value in 2004. The difference was attributed to structures added and renovations/improvements of existing structures since the report date. However, unlike residential property, commercial development since 1997 could not necessarily be assumed to take place at or above the 100-year flood plain. To varying extent, “new” commercial property value includes replacement, renovation, and/or improvement of older, antiquated structures. Since data were not readily available to sort out the amount of value due to renovation and improvement versus structures built at new sites, the difference between report values and 2004 values were allocated across all FSDF elevations. The allocations were based on the ratio of damages at that elevation to the report date aggregate property value.

Forecasting Residential Flood Stage Damage Functions

Flood-stage damage functions were estimated annually for each city for 2006 through 2055 by using future aggregate commercial and residential property values as a proxy to adjust future damage levels within the flood-stage damage functions. The approach assumes that generally as the aggregate value of property increases in a community, the potential damages from a flood also increase, providing no additional flood protection measures are implemented. The approach also assumes that real property values, both commercial and residential, are correlated with population and are subject to time trends. The forecasted property values for each year (2006 through 2055) are then given as:

(4) Aggregate real property value$_t$ = (Intercept + per capita aggregate property value trend × year) × population$_t$.

To project future levels of damages within the FSDFs based on changes in aggregate property values, the time trend in per capita aggregate property values was estimated using regression. Historical nominal property values were expressed in real (2004 dollars) terms using the real housing index. Real aggregate residential property values were divided by population to obtain a 15-year series on real per capita aggregate residential property values. Regression analysis was then used to determine the time trend in the per capita values (Table 5). The same procedures were used with commercial property and yielded time trends in real per capita aggregate commercial property values in each study community (Table 6). Statistically significant time trends in per capita aggregate residential property values were found for all six study cities. Positive trends were found for all cities except Drayton. Forecasting the negative per capita trend in Drayton with future population resulted in zero property values in year 2048 and thereafter. This result was suspect and real per capita residential property values were held constant at the 10-year historical average for Drayton[5].

---

[5] Regardless of approach, the influence of changes in Drayton’s property values on the final results is negligible.

Table 5. Results of Regressions of Per Capita Residential Real Property Values, 1990 through 2004

City	n	Intercept	Year Coefficient	Standard Error	R^2
Fargo	15	-1315438.741	667.636	31.381	0.97
Moorhead	15	-1705428.304	865.466	68.056	0.93
Grand Forks	15	-1343944.804	682.857	52.304	0.93
East Grand Forks	15	-1886808.363	955.466	56.029	0.96
Wahpeton	15	-289908.628	151.321	24.359	0.75
Breckenridge	15	-741677.4	382.989	104.596	0.51
Crookston*	12	358818.249	-170.333	105.605	0.21
Drayton	10	539187.782	-262.71	93.865	0.5
Grafton*	15	-252811.38	133.528	34.51	0.54

* Data were collected for Crookston and Grafton but the impact of the Waffle on flood stage for those cities was not available.

Table 6. Results of Regressions of Per Capita Commercial Real Property Values, 1990 through 2004

City	n	Intercept	Year Coefficient	Standard Error	R^2
Fargo	15	-1196918.687	605.795	54.952	0.9
Moorhead	15	-414347.435	209.546	24.541	0.85
Grand Forks	15	-1160266.833	586.945	46.46	0.93
East Grand Forks	15	-404246.482	204.838	20.176	0.89
Wahpeton	15	-512098.736	259.969	28.044	0.87
Breckenridge	15	-353733.808	178.445	5.893	0.99
Crookston*	12	-345225.907	174.516	11.492	0.96
Drayton	10	9436.626	-2.624	16.489	0
Grafton*	15	-258304.401	132.379	29.336	0.61

* Data were collected for Crookston and Grafton but the impact of the Waffle on flood stage for those cities was not available.

For per capita commercial property value, only Drayton's trend was insignificant. Again, Drayton's real per capita commercial property value was held constant at the ten-year historical average value.

Population projections for each city also were collected for the same period (2006 through 2050) (see Appendix C). Population projections for 2051 through 2055 represented extrapolations of the change in population from 2045 to 2050. The trend in per capita values (i.e., regression results) were multiplied by long-term population forecasts to estimate future aggregate residential and commercial property values for each year of the 2006 through 2055 period.

To forecast the FSDFs, damages at each elevation were annually adjusted to reflect (real) changes in existing property values. This was a two step process. First, a trend in real property values was determined using the OHFEO index to account for the increase in real property value. The annual percentage change in real property values, as estimated by the trend, was used to adjust damages at each elevation. For example, if an elevation of 900 feet (msl) had damages of $120 million in 2008 and the trend shows a 1.2 percent increase in real property values, the damages at 900 feet in 2009 were forecasted at $121.4 million ($120 million × 1.012).

The next step in the process was to incorporate the effects of changes in population into the damage estimates. Equation (4) was used to forecast aggregate residential property values for each city annually from 2006 through 2055. Given that aggregate residential property value and the change in existing residential property value had been forecasted, the change in housing value due to new homes was estimated by subtracting the change in the value of existing structures from the change in aggregate housing value. Or by rewriting equation (3), the change in housing value due to new homes can be expressed as:

(5) $\text{New construction}_t = \Delta\text{Aggregate property value}_t - \Delta\text{existing property value}_t$.

Existing property values were projected annually from 2006 through 2055. Time-trends were estimated for the annual real housing indices (Table 7). In equation (6), the estimated annual real housing index is given as:

(6) $\text{Real housing index}_t = \text{intercept} + \text{trend} \times t$.

The real housing indices were forecasted annually to 2055. The percentage change in the forecasted values was multiplied by real housing values from year t-1 to find housing values in year t, or

(7) $\text{Real housing value}_t = \text{Real housing value}_{t-1} \times$ percentage change in forecasted real housing index.

When the annual changes in equation (7) are computed, the results can be used in equation (5) to find the forecasted value of newly constructed homes.

Table 7. Time Trend Analysis for Real Housing Index, 1990 through 2004

City or State	n	Intercept	Year Coefficient	Standard Error	R^2
Fargo/Moorhead	15	-3912.075	2.027	0.272	0.810
Grand Forks/East Grand Forks	15	-2914.471	1.525	0.292	0.678
North Dakota	15	-5172.556	4.735	0.283	0.874
Minnesota	15	-18859.922	9.586	0.986	0.879

Given the assumption that new residential construction occurs at or above an elevation equal to the 100-year flood frequency, additional flood damages from new structures were allocated to the FSDFs starting at the 100-year flood frequency. It was assumed that the relative portion of incremental damages at each flood stage remained constant as total potential damages increased. Two steps were required to assign the incremental damages to each flood stage. First, damages were compared at each elevation above the 100-year frequency to damages at one foot below the 100-year flood frequency. The difference between these values was divided by total residential property value to arrive at a percentage. Second, that percentage was multiplied by the value of new residential properties constructed in each year (2006 through 2055). The resulting value was added to damages at that elevation from the previous year. For example, consider the FSDF for Fargo/Moorhead in Table 4. From the table, the flood stage one foot below the 100-year event is 900 feet msl which corresponds to $277.6 million in damages. The damages at 901 feet msl are $543.4 million. If it is assumed that total property value is $5 billion in year 2008, the incremental damages are 5.32 percent (($543.4 million - $277.6 million)/$5 billion) of aggregate property value. If $20 million of new housing value (i.e., due to population change) is added in 2008, then it is assumed that damages at 901 feet msl will increase by $1,063,488 (0.0532 × $20 million). This process is then repeated for each elevation above the 100-year frequency. As elevation above the 100-year frequency increases, so does the percentage and the allocation of incremental damages at that elevation. The entire process is repeated annually from 2006 through 2055.

Forecasting Commercial Flood-stage Damage Functions

To forecast future commercial FSDFs, increases in damages from existing structures and new damages due to additional structures had to be incorporated. However, since new construction was assumed to occur at all elevations in the study communities, it was only necessary to project total commercial property values annually. Separate adjustments to damages at or above the 100-year frequency were not necessary. As with residential property, adjustments for the commercial FSDFs involved 1) computing the time trend in real per capita aggregate commercial property values; 2) projecting that trend annually from 2006 through 2055; and 3) multiplying the projected trend by population forecasts to estimate aggregate commercial property values from 2006 through 2055. The relative damages associated with each elevation in the FSDFs were held constant across the 50-year time horizon. For example, if damages at the 100-year frequency were 10 percent of aggregate commercial property value in 2006, then 10 percent of total estimated aggregate commercial value in 2006 was assigned to the damages at the 100-year frequency. The same procedure was performed for each year forecasted (i.e., 2006 through 2055).

Damages accruing to public infrastructure were contained within the commercial flood-stage damage functions for some cities and were provided as separate flood-stage damage functions for other cities (see Table 3). Future values for the amount of flood damages to public infrastructure were generally assumed to parallel the level of flood damages associated with residential and commercial properties. Thus, as a community changes population over time, the potential change in flood damages to public infrastructure was assumed to be proportionate to the potential changes in flood damages associated with residential and commercial property.

No attempt was made to tie future damages to changes in the level of personal and/or business property in the study communities. Whatever proportion of expected damages that were represented by loss of personal property (e.g., furniture, appliances, other belongings) and business property (e.g., computers, office equipment, inventory) within the functions was retained as the future expected damages were forecasted. In other words, damages were not adjusted up or down to correspond with an increase/decrease in the relative value (ratio of the value of personal belongings and business property compared to the value of residential and commercial structures) of property at risk.

Improvements in Structural Flood Protection

Finally, improvements in structural flood protection developed since 1997 are incorporated into the FSDFs. Various structural improvements have been implemented or are being implemented in Grand Forks/East Grand Forks and Wahpeton/Breckenridge. Flood damages below the level of protection for those projects were set to zero, which is consistent with the definition of damages set forth by the USACE. No adjustments for new protections were necessary for the FSDFs in Fargo/Moorhead and Drayton.

Expected Future Damages

After updating the FSDFs for each area, the expected damages before and after implementing the Waffle are computed using integration. Implementation of the Waffle decreases the frequency of various flood heights. The EERC Waffle research project estimated the change in flood crest heights associated with Waffle implementation. These crest reductions were estimated for various flood crest heights for both the full- and half-scale Waffle scenarios under two water storage capacities. Waffle data from the EERC also represented points on the FSDF, and remaining crest reductions for other points on the curve were estimated using interpolation. Changes in frequency came from integration of flood probabilities in the model, which was a result of a new set of flood crest heights tied to the original USACE data on flood frequencies.

Expected damages both with and without the Waffle are computed using equation (2) for each year (2006 through 2055). The expected annual benefits from the Waffle are computed as annual difference in expected damages without Waffle and with the Waffle. This difference is computed for each of the 50 years, discounted to 2006 dollars and summed, generating the total discounted benefits.

Costs

A deterministic model was developed to estimate the costs of operating the Waffle over a 50-year period. Key parameters and inputs for the model included landowner payment structures; landowner payment rates (percentage of expected future cash rents); structural, installation, and maintenance costs for culvert control devices; payment acreage by land type, relief category, county, and Waffle scale; administration expenses, enrollment costs, inflationary factors, and a discount rate. The model was designed to provide estimates of the present value of Waffle costs over a 50-year period for a range of physical and economic values. Since the model is deterministic, adjustments in the values of key cost factors were used to determine the sensitivity of costs to changes in input factors. A brief description of cost inputs and parameters is described in the following sections.

Culvert Modification, Installation, and Annual Maintenance Costs

Culvert devices designed for the Waffle were estimated by the EERC to remain operational for approximately 50 years. Since the expected life of the control devices was estimated to equal the time frame for evaluating the Waffle, culvert modifications and installation expenses were considered a one-time expense, incurred in the first year of the 50-year evaluation period. It is acknowledged that some additional removal and installation expenses are likely to occur at the end of any contract period as some land tracts exit the Waffle (i.e., not re-enroll) or as other land tracts enter the Waffle (i.e., enroll for the first time). These potential expenses were not modeled.

Basically, the amount of land by relief category was the primary factor influencing the culvert modification and installation expenses within the model. The EERC provided cost estimates for culvert modifications for land sections delineated by three relief categories for three watersheds in the Red River Basin (see Appendix B). Based on the work conducted by the EERC, the cost of culvert modifications and installation expenses varied by relief category per section, and was not considered to change by land classification. A single set of anticipated modification and installation expenses were used in the model and were based on data from the Red Lake Watershed (see Appendix B). Thus, the overall cost for culvert modification and installation expenses for the Waffle were based on the number of sections of land by relief category. Data on the number of sections of land by relief category for each acreage option for each scale scenario were provided by the EERC.

While culvert modifications and installation expenses were considered one-time expenses, due to a host of potential circumstances, those devices were considered to require periodic maintenance, inspection, and repair. Expenses for periodic maintenance, inspection, and repair were collectively called maintenance costs, and were simply expressed annually as a percentage of culvert modification and installation costs since data were not available to suggest a more appropriate level for those expenses. Each year's maintenance cost was based on applying the inflationary factor to the previous year's maintenance cost, thereby allowing those costs to increase over time.

Waffle Scale, Acreage, and Landowner Payments

Two Waffle scales were considered. The EERC provided three acreage estimates for each Waffle scale (see Appendix A). The combinations of scale and acreage resulted in six different estimates of the physical 'footprint' of the Waffle. Each acreage option within the full- and half-scale sizes determines the number of payment acres by land classification, relief category, county, and state (see Appendix A).

Three different payment structures to landowners were incorporated into the model: 1) payments are made only during years when fields are flooded; 2) payments are made every year regardless of whether water is stored; and 3) payments represent a combination of annual and flood-event compensation. An additional approach used in the cost model was to assume that the Waffle would require landowners to agree to some contract period whereby the land would remain available to be used in the Waffle. The model was designed to provide for a retainer payment at the beginning of each contract period. For example, if contract periods were to last 10 years, then a landowner(s) of a single tract of land could receive 5 retainer payments, one every 10 years, assuming the land tract remained in the Waffle over the 50-year period. Retainer payments were allowed to vary based on a percentage of cash rent. Contract length and the level of retainer payments were both input variables in the model.

Another factor which influences the estimation of landowner compensation was a minimum flood frequency or flood-event size that resulted in the Waffle storing water. Early on in the analysis it was realized that it would make little economic sense to use the Waffle to mitigate flood damages for relatively minor spring-time flood events. However, this approach implies that the appropriate government agencies would have sufficient predictive capacity to know when the Waffle would be required to mitigate flooding in the Red River Basin. Flood frequency was used to adjust the level of landowner payments to account for the annual probability of water storage. For example, if the Waffle is only used on a 50-year or larger flood and the landowner was to receive $75 per acre that year for water storage, the model estimated a payment that year for $1.50 per acre (1/50 x $75). This same procedure was repeated annually except that payments would change as cash rents were allowed to increase over time. The flood frequency used in the cost model was tied to the smallest flood size used by the EERC to evaluate flood crest height reductions.

Landowner payments were generated for all payment acreage in the Waffle. When the Waffle stores water, it was assumed that all tracts would be used for that flood event. Although it would be possible for the Waffle to selectively choose tracts of land to store water on depending upon local conditions for any particular flood event, the cost model assumes all land receives a payment in all flood events. This assumption is consistent with the perception that Waffle has the most potential to mitigate the effects of larger floods.

Enrollment and Administrative Costs

The model allows for costs associated with enrolling land in the Waffle and administration of the Waffle. Enrollment expenses were included to approximate a cost for conducting meetings, performing outreach efforts to educate landowners, producers, and the general public, and provide some expense for drawing up legal contracts, negotiations, filing easements, and any other expense associated with enrolling land in the Waffle and making the Waffle operational. Unfortunately, information was not available on what those expenses would likely be, so initial enrollment expenses were modeled as a flat dollar rate per section. The bulk of enrollment costs were modeled as one-time expenses at the beginning of the 50-year period. Additional enrollment expenses could be expected at the beginning of each contract period. However, enrollment costs after the first contract period were considered minimal compared to the costs covered by enrollment expenses at the beginning of Waffle operation, and were estimated as a percentage of the expenses incurred at Waffle startup. The reoccurring enrollment expense coincided with the length of contract.

Estimates of the cost to administer the Waffle were not available, nor was secondary data available to provide a proxy for those expenses. It would be anticipated that administration expense, after all land enrollment is complete and the Waffle is fully functional, would likely be relatively moderate for most years, but that costs could be substantial in years when the Waffle actually stores water. Administrative expenses would obviously be greater during the years when the Waffle is used due to the resources needed to distribute landowner payments, assess status of devices, monitor water storage levels, record water flows and volumes, review and/or modify operational procedures, mitigate any unforeseen local problems with water storage, provide controlled release of stored water, and so on. For simplicity, an average annual amount of administrative expense was modeled. However, since it could be argued that some administrative functions could increase as the work load and complexity increases with Waffle scale, an additional amount of administrative expense was modeled as a function of Waffle scale. The additional expense was a flat monetary rate tied to Waffle acreage.

Study Limitations

The goal of this study was to provide a first assessment of the cost-effectiveness of the Waffle. As additional data becomes available and as the level of understanding of the Waffle improves, a number of refinements in the benefits and costs of the Waffle would be warranted. These improvements could stem from including material previously omitted, applying alternative estimation techniques, and/or refining existing baseline data to more accurately reflect an evolving understanding of how the Waffle would be implemented and operated. The following discussion highlights some of the data and methodological limitations of this study.

Estimation of Benefits

This study used a conservative estimate of the potential benefits of the Waffle. Benefits of the Waffle were limited to mitigated flood damages in seven communities in the Red River Basin. Additional benefits that could be examined in future assessments include the following.

1) Mitigated flood damages to rural homes, farmsteads, and agricultural buildings, as well as mitigated damages to the numerous small communities located along tributaries and the Red River.

2) The beneficial economic effects of reduced probability of levee failure associated with lower crest heights. Also, the savings or benefits associated with extending the useful life of existing flood protection measures that may result from the Waffle.

3) Potential long-term agronomic or economic benefits to agricultural land resulting from temporary water storage.

4) Potential economic benefits to groundwater recharge, improved water quality, reduced soil erosion, or other environmental benefits.

5) Mitigated flood damages that might occur within the Canadian portion of the Red River Basin as a result of the Waffle being used in the U.S. portion of the basin.

6) Mitigated flood damages associated with rural roads, bridges, and other public infrastructure not contained in existing functions. Also, economic benefits accruing from the prevention of road closures on rural, state, or federal transportation systems.

7) Reduction in costs associated with implementing preventive measures tied to the removal, relocation, or handling of toxic, hazardous, or sensitive materials prior to impending floods.

8) Possible reduction in Federal Flood Insurance costs and or the potential to remove or redefine flood plain designations.

Refinements in the estimation of the flood-stage damage functions would be valuable for future assessments of the Waffle. A re-estimation or re-calculation of the flood-stage damage functions for nearly all of the communities included in the study would improve the potential estimation of mitigated flood damages. While the flood-stage damage functions used in this study were current with respect to existing flood protection measures in all of the cities, the flood-stage damage functions could be improved if they were updated to include recent changes in the location and value of residential, commercial, and public infrastructure. While attempts were made in this study to update flood-stage damage functions for changes in the value of residential, commercial, and public infrastructure at risk for flooding using secondary data, the flood-stage damage functions would be more accurately updated if new primary data were used with the USACE estimation techniques.

Estimation of Costs

The following limitations/refinements apply to cost estimates.

1) Costs of culvert modifications throughout the basin were based on the costs associated with a single watershed. An improvement would be to include separate estimates of the likely costs of culvert modifications for each watershed in the Red River Basin or more closely tie the costs of culvert modifications to local conditions, regardless of watershed considerations.

2) Cash rents on agricultural cropland were used as a proxy for estimating financial compensation on non-agricultural lands enrolled in the Waffle. While the amount of non-agricultural land in the Waffle is minor compared to agricultural land, future economic assessments of the Waffle may benefit from using other approaches to estimating the level of financial compensation needed for non-agricultural lands.

3) Maintenance costs for the culvert modifications should be based on engineering assessments of the rate of failure over the life of the devices. Data on the cost of labor and materials to periodically monitor, maintain, and occasionally repair the control devices are currently unavailable.

4) Administrative expenses could be refined as the operational and overhead requirements of the Waffle are better understood. Would an operational Waffle-based flood mitigation

strategy require a regional headquarters? Would there be satellite offices located throughout the basin? What would be the basin-wide staffing requirements to monitor and operate the Waffle? What additional resources would be required to insure that the Waffle operates efficiently during spring floods?

5) The cost of getting the Waffle implemented is largely unknown, and those expenses could be more accurately estimated with additional information. At this point, the resources needed to educate the public, develop and design landowner contracts, resolve possible legal obstacles, address any legislative issues, resolve any international conflicts, and handle any other unforeseen aspects of developing and implementing the Waffle are not well understood. Would a pilot Waffle be first implemented in a single watershed, with the lessons learned being applied throughout the basin? What might be a realistic time line to implement the Waffle basin wide?

6) Current information on the level, frequency, and nature of landowner compensation needed to make the Waffle operational is insufficient, and details on those issues are likely to remain elusive until more information is known about 1) the physical effects of temporary water storage and 2) how participation in the Waffle may affect other income sources (e.g., crop insurance payments, farm program provisions). From a planning perspective, some fundamental issues remain unanswered. What level of compensation is necessary to entice landowners to enroll? Does the level of compensation need to be correlated with the length of time water is stored? What effect will contract design have on the willingness of landowners to cooperate in the Waffle? Also, the issue of compensation rates and volume of water stored on any given land tract raises questions on economic efficiency of enrolling land in the Waffle. A more thorough understanding of the interaction between landowner compensation and willingness to enroll, economic efficiency of water storage, landowner contract design, and other related issues is likely to require additional research.

7) Landowner compensation was based on payment acreage, which was held constant regardless of the size of flood event. If the amount of payment acreage changes with the size of flood event, then estimates of landowner compensation should also be tied to the size of flood event. Conceptually, all acreage enrolled in the Waffle may not be needed or may not be used to temporarily store runoff with smaller-sized flood events, especially if flood severity for any particular event is unequal throughout the Basin. If the amount of acreage flooded by the Waffle varies, then it is possible that payment acreage could also vary. If payment acreage actually varies by size of flood event, then it is likely that landowner compensation is overstated with smaller-sized flood events. Since smaller-sized flood events are likely to occur more frequently, and smaller-sized flood events could potentially have less payment acreage, the ability to refine landowner compensation based on flood size could greatly improve cost estimates. The capacity to tie payment acreage more closely to the size of the flood event would provide a refinement in the cost estimates associated with the Waffle.

8) Data were not available to differentiate Waffle acreage within a county for purposes of adjusting payment levels associated with potential variations in cash rent. All payments for land in each county were tied to a single level (i.e., average value) for cash rent in that county. Using an average value for all Waffle acreage in a county results in compensation rates being higher in some situations and lower in other situations than if payment levels were more closely tied to local conditions. A potential refinement in estimating landowner compensation would be to use more localized cash rents for land in the Waffle, rather than using county average cash rents.

RESULTS

This report provides a first assessment of the cost-effectiveness of the Waffle and provides insights into the economic feasibility of using the Waffle to mitigate flood damages in the Red River Basin. The results presented in the following sections should be considered under the context that a considerable amount of uncertainty and knowledge gaps remain on both the cost and benefit aspects of the Waffle. A refinement in those data gaps and a reduction in many of this study's limitations would increase the confidence in the economic analysis.

Benefits were estimated for the appropriate combinations of Waffle scale, storage volumes, and population projections. The analysis produced 12 estimates of the level of Waffle benefits. However, a discrete number of cost estimates would require a subjective number of values to be used for many cost factors. As a result, a reasonable range of values for some cost factors was used to limit the number of cost estimates for the Waffle. Total costs of operating the Waffle are presented, along with a separate section for gross benefits. Finally, total costs and gross benefits are combined.

Costs

The costs of operating the Waffle over a 50-year period are provided in present value terms (i.e., future costs discounted to the present time). For sake of limiting the potential number of estimates of the cost of operating the Waffle, a baseline scenario was developed using reasonably acceptable values for cost inputs, given current knowledge about the Waffle. While the baseline scenario produced a cost estimate for each combination of Waffle scale and payment acreage, cost inputs were adjusted to reflect a more economically favorable scenario and a more economically unfavorable scenario (Table 8).

The input values that remained unchanged across all cost scenarios were a 5 percent discount rate, a 10-year contract period, an 11-year or larger flood event for using the Waffle, and landowners received payments only when water was stored (not including retainer payments).

For the baseline cost scenario, values for key economic variables included $1,500 per section for enrollment expenses, retainer payments equal to 125 percent of cash rent, water storage payment rates equal to 175 percent of cash rent, maintenance costs equal to 1 percent of the cost of culvert control devices, administrative expenses starting at $250,000 per year with an additional $2 for every 100 acres enrolled, and annual inflation rate of 2.75 percent (Table 8).

The key variables that were adjusted between optimistic and pessimistic cost scenarios were enrollment expense, retainer payment, water storage payment, maintenance, administrative expense, and inflation rate (Table 8).

Table 8. Input Values for Key Variables and Parameters for Baseline, Optimistic, and Pessimistic Scenarios on Waffle Operation Costs, 50-year Period

	Value used for Input Variables		
Input Variable[a]	Optimistic Scenario	Baseline Scenario	Pessimistic Scenario
Enrollment cost per section (startup)	$1,000	$1,500	$2,000
Enrollment cost per section (at end of each contract period)	15% of costs at start-up	25% of costs at start-up	40% of costs at start-up
Landowner retainer payment per acre per contract (percent of cash rent)	100%	125%	150%
Length of enrollment contract	10 years	10 years	10 years
Cash rent on 'other' land (percent of cash rent on cropland)	50%	75%	100%
Landowner payment per acre when water is stored (percent of cash rent)[b]	125%	175%	250%
Flood-event frequency when Waffle is used	11-year event	11-year event	11-year event
Average administrative expenses per year	$200,000	$250,000	$350,000
Additional administrative expense based on Waffle scale	$0.10 per acre	$0.20 per acre	$0.30 per acre
Annual culvert maintenance cost as a percentage of the value of culvert devices	0.5%	1%	2%
Inflationary adjustment for administrative and maintenance costs	2.5% per year	2.75% per year	3% per year
Discount rate	5%	5%	5%
Cost per section for culvert control devices by relief category			
0 - 2	$11,600	$12,700	$14,500
2 - 4	$9,400	$10,300	$11,700
4 - 10	$3,600	$4,000	$4,500
Installation cost per section for culvert control devices by relief category			
0 - 2	$1,200	$1,320	$1,500
2 - 4	$1,000	$1,100	$1,250
4 - 10	$800	$880	$1,000

[a] Detailed description of cost variables can be found on pages 27 through 29.

[b] Payments made only when water is stored.

Cash and discounted (i.e., present value) costs were generated to gauge the relative influence of default input values on the overall cost structure for the Waffle (Table 9). A considerable difference exists between the cash and discounted values for expenses, depending upon what point during the 50-year period the expense was predicted to occur. For example, maintenance costs, which are modeled to occur each year, represent nearly $48 million in cash costs, but only represent $14.5 million in present value costs. Overall, cash costs of operating the Waffle would be about 2.5 to 3 times higher than present value costs (Table 9).

Table 9. Total Cash and Discounted Costs Associated with Input Values, Baseline Scenario, Full-scale Waffle with Maximum Acreage, 2006 through 2055

Input Variable	Input Value	Cash Costs[a]	Present Value[b]
Enrollment cost per section (startup)	$1,500	$7,184,000	$6,841,000
Enrollment cost per section (at end of contract period)	25% of costs at start-up	$7,182,000	$2,333,000
Landowner retainer payment per acre per contract (percent of cash rent)[c]	125%	$533,967,000	$222,812,000
Landowner water storage payment per acre (percent of cash rent)[d]	175%	$704,883,000	$238,331,000
Minimum administrative expenses per year	$250,000	$26,203,000	$7,349,000
Additional administrative expenses based on Waffle scale	$0.20 per acre	$29,652,000	$8,317,000
Annual culvert maintenance cost as a percentage of the value of culvert devices	1%	$47,982,000	$13,458,000
Culvert devices and installation per section by relief contour		$45,779,000	$43,599,000
0 - 2	$14,020		
2 - 4	$11,400		
4 - 10	$4,880		
	Totals[e]	$1,402,832,000	$543,041,000

[a] Cash expenses were not discounted and represent sum of expenses over 50-year period.

[b] Expenses discounted annually at a rate of 5 percent.

[c] Based on 10-year contract period.

[d] Waffle used at 11-year flood event or larger.

[e] Waffle size equal to 1,414,560 payment acres.

Baseline Cost Scenario

The baseline cost scenario represented an attempt to provide a cost projection that was not overly pessimistic or optimistic. In some cases, values for various inputs represented best estimates or best guesses and were considered reasonable, given data and knowledge limitations. The present value of costs for the full-scale Waffle for the baseline scenario ranged from $543 million with maximum acreage to $208 million with minimum acreage (Table 10). The present value of costs for the half-scale Waffle for the baseline scenario ranged from $275 million with maximum acreage to $108 million with minimum acreage. Across both the full- and half-scale Waffle sizes, the largest expense was for payments to landowners, followed by equipment and installation expenses associated with the culvert control devices (Appendix E contains Waffle expenses by category for each cost scenario).

Table 10. Present Value of Projected Costs of the Waffle, 2006 through 2055

Scale and Acreage Estimate	Cost Scenarios		
	Baseline	Optimistic	Pessimistic
	----------------------------- 000s $		----------------------------
Full-scale			
Minimum	207,931	155,739	287,326
Moderate	362,191	269,537	494,872
Maximum	543,040	402,721	738,602
Half-scale			
Minimum	107,964	80,915	149,494
Moderate	184,797	137,578	252,897
Maximum	275,505	204,386	375,132

Optimistic Cost Scenario

A number of values for input variables and parameters were adjusted to reflect an optimistic set of expectations regarding the operational costs of the Waffle to provide some lower bounds of the costs associated with the Waffle. Essentially, in the optimistic cost scenario it was less costly to get the Waffle operational and less costly to compensate landowners (i.e., relatively lower retainer and water storage payments). Other cost reductions came from slightly lower administrative overhead and more favorable long-term inflation rates.

The present value of Waffle costs under the optimistic cost scenario with the full-scale size ranged from $403 million with maximum acreage to $156 million with minimum acreage (Table 10). With the half-scale size, costs of operating the Waffle ranged from $204 million for maximum acreage to $81 million with minimum acreage.

Waffle costs for the full-scale option with maximum acreage were projected to decrease by 26 percent from the baseline scenario to the optimistic scenario ($543 million down to $403 million) (Table 10). In the half-scale option, Waffle costs for the maximum acreage in the baseline scenario also decreased by 26 percent in the optimistic scenario ($276 million compared to $204 million) (Table 10).

Pessimistic Cost Scenario

Several inputs and parameters were adjusted to reflect an pessimistic set of expectations regarding the operational costs of the Waffle to provide some upper bounds of the costs of the Waffle. The cost inputs that were adjusted in the pessimistic scenario included the level of retainer payments, water storage payments, maintenance costs, inflationary factors, and enrollment and administration costs (see Table 8).

Waffle costs for the full-scale option with maximum acreage were projected to change from $543 million in the baseline scenario to $739 million in the pessimistic scenario (Table 10). The change represented a 36 percent increase in costs compared to the baseline scenario. In the half-scale option, Waffle costs for the maximum acreage in the baseline scenario were estimated at $276 million, compared to $375 million in the pessimistic scenario (Table 10).

Gross Benefits

Unlike the cost model, the benefits model did not contain the same degree of flexibility to adjust all input variables or parameters. The factors that did change in the estimation of benefits included future population projections and estimated changes in river crest heights associated with Waffle scale and anticipated storage volumes. Three population projections were used to adjust the damage values in the FSDFs for future population changes in the study communities. For each population projection, four possible sets of crest height reductions were used. Estimated reductions in crest heights were generated by the EERC for the full-scale and half-scale implementation of the Waffle with moderate and conservative water storage scenarios for each scale. The combination of population projections, Waffle scale, and water storage scenarios produced 12 estimates of Waffle benefits.

Crest Height Reduction

The EERC estimated the hydrologic and hydraulic effects of water storage from the Waffle on the intensity of spring floods throughout the Red River Basin. One of the results of this fundamental analysis of the Waffle's performance was the estimated difference between crest heights on the Red River without the Waffle and crest heights with the Waffle. The change in crest heights for the Red River at key locations provided a measure of the performance of the Waffle in reducing the intensity of a flood event. The change in flood intensity, measured by a change in crest height, could then be used with the FSDFs to estimate mitigated flood damages (benefits).

The EERC evaluated the performance of the Waffle using full-scale and half-scale scenarios with a moderate and conservative estimate of water storage capacity for each scale. A number of considerations and assumptions went into the analysis of both the moderate and conservative water storage capacities for the Waffle. The factors considered and the values used for those analyses are highlighted in Appendix F. Since the primary data for the analysis of the Waffle's potential performance on reducing crest heights along the Red River came from the 1997 flood, several flood event sizes were developed that were based on derivatives (i.e., percentages) of the water flows present in 1997. The Waffle was evaluated for the following flood events: 50 percent of 1997, 100 percent of 1997, 125 percent of 1997, 150 percent of 1997, and 200 percent of 1997. Since the 1997 flood was not considered the same event size at all locations in the Red River Basin, the frequency for the flood events modeled by the EERC also varied by location (Table 11). The key locations along the Red River included Wahpeton/Breckenridge, Fargo/Moorhead, Grand Forks/East Grand Forks, and Drayton. Estimates of crest height reductions were not generated for other locations along the Red River and for other tributaries in the Basin.

Table 11. Approximate Frequency of Flood Event Sizes Evaluated for Waffle Flood Reduction

Flood Event Evaluated	Estimated Flood Frequency (years)[a]			
	Fargo / Moorhead	Grand Forks / East Grand Forks	Wahpeton / Breckenridge	Drayton
50% of 1997	21	11	25	25
1997	122	130	241	278
125% of 1997	251	338	893	>10,000
150% of 1997	500	1250	1160	>10,000
200% of 1997	>10,000	>10,000	>10,000	na

[a] Frequency based on USACE data. Derivatives of 1997 flood are not linear.

NA=not available.

The Waffle was estimated to reduce crest heights by a few tenths of a foot to several feet, depending upon flood event size, Waffle scale, water storage assumptions, and location along the Red River (Table 12) (Appendix F). Of particular interest would be the effect of the Waffle on 1997 flood crest heights, since the 1997 flood can serve as a real world reference for most individuals. In Wahpeton/Breckenridge, the Waffle was estimated to reduce the Red River crest height by 0.15 feet (conservative storage under half-scale Waffle) to 1.92 feet (moderate storage under full-scale Waffle) for conditions present during the 1997 flood. By contrast in Fargo/Moorhead, the Waffle in 1997 would have reduced the crest height on the Red River by 3.91 feet (conservative storage under half-scale Waffle) to 6.17 feet (moderate storage under full-scale Waffle). In the case of Fargo/Moorhead, the anticipated crest height reductions appear to be substantial. Similar magnitude of change could have occurred in Grand Forks/East Grand Forks in 1997, where the Waffle could have reduced the crest height of the Red River by 0.67 feet (conservative storage under half-scale Waffle) to 4.97 feet (moderate storage under full-scale Waffle). A 5-foot lower crest height in Grand Forks/East Grand Forks in 1997 would likely have been sufficient to spare the metro area from the catastrophic damage of that flood.

Table 12. Estimated Crest Heights of Red River With and Without the Waffle at Key Locations, by Waffle Scale, Flood Event Size, and Water Storage Scenarios

Flood Event Size	River Crest Heights (feet)				
		Conservative Water Storage		Moderate Water Storage	
	No Waffle	Half-scale	Full-scale	Half-scale	Full-scale
	------------------------------ Wahpeton/Breckenridge ------------------------------				
50% of 1997	17.54	17.23	16.81	16.14	15.2
1997	23.43	23.28	23.01	22.42	21.51
125% of 1997	25.8	25.67	25.4	24.86	23.97
150% of 1997	27.89	27.8	27.56	27.14	26.23
200% of 1997	31.56	31.56	31.33	30.93	30.14
	--------------------------------- Fargo/Moorhead ---------------------------------				
50% of 1997	33.01	29.19	28.49	27.26	25.32
1997	39.94	36.03	35.57	34.81	33.77
125% of 1997	41.87	38.5	38.11	37.39	36.2
150% of 1997	43.25	40.59	40.19	39.56	38.49
200% of 1997	45.35	42.94	42.76	42.35	41.67
	------------------------- Grand Forks/East Grand Forks -------------------------				
50% of 1997	45.22	44.01	42.68	40.36	36.03
1997	54.2	53.53	52.7	51.23	49.23
125% of 1997	57.61	57.15	56.33	54.97	52.99
150% of 1997	59.77	59.59	59.22	58.19	56.33
200% of 1997	62.55	62.46	62.07	61.4	60.44
	------------------------------------- Drayton -------------------------------------				
50% of 1997	42.63	42.02	41.43	40.58	38.91
1997	47.31	47.01	46.61	45.93	44.95
125% of 1997	48.96	47.74	48.38	47.77	46.85
150% of 1997	50.37	50.2	49.86	49.31	48.47
200% of 1997	na	na	na	na	na

Source: Kurz et al. (2007).

Baseline Growth Scenario

The baseline scenario was evaluated based on a population projection for the study communities. Future population was a key input affecting the level of potential damages that could occur in the study communities. Obviously, all things equal, an increase/decrease in population would translate to more/less property at risk from flood related damage. The more potential damage, the greater the potential for mitigated flood damages (benefits) associated with the Waffle.

The present value of the benefits of the Waffle ranged from $605 million with conservative water storage capacities with the half-scale Waffle under the baseline population scenario to $915 million with moderate water storage capacities with the full-scale Waffle (Table 13). Obviously the greater reductions in crest heights found with the moderate water storage capacities in each Waffle scale translated to greater mitigated flood damages in the study cities. Approximately $250 million in benefits separated the moderate and conservative water storage assumptions for the full-scale Waffle whereas about $200 million separated benefits for the half-scale Waffle in the baseline population scenario (Table 13).

Table 13. Present Value of Gross Benefits of the Waffle, 2006 through 2055

Scale and Water Storage Estimates	Population Scenarios		
	Baseline	Optimistic	Pessimistic
	----------------------------- 000s $ ----------------------------		
Full-scale			
Moderate	914,790	1,020,861	885,019
Conservative	668,226	752,846	652,444
Half-scale			
Moderate	811,629	907,900	786,914
Conservative	605,554	684,309	592,929

Optimistic Growth Scenario

The optimistic population scenario was based on projections for growth in population in Fargo, Grand Forks, Breckenridge, East Grand Forks, and Moorhead. For Drayton and Wahpeton, the main and optimistic projections were unchanged since population growth data consistent with the conditions used in the main population forecast could not be found. The greatest numerical change in population between the two forecasts was found in Fargo and Moorhead (see Appendix C). The optimistic scenario resulted in an 18 percent increase in population in the four study communities over the population projections found in the baseline scenario. The use of the optimistic scenario was to demonstrate that population increases can affect the future expected benefits of the Waffle. Granted, the location of the population growth can also influence the results, since current property values, past trends in property values, and existing flood protection measures all differ for the study communities.

The present value of the gross benefits of the Waffle ranged from $670 million with conservative water storage capacities with the half-scale Waffle to $1 billion with moderate water storage capacities with the full-scale Waffle (Table 13). An 18 percent increase in population between the main and optimistic scenarios produced 11 to 13 percent increases in mitigated flood damages. Over $250 million in benefits separated the moderate and conservative water storage capacities in the optimistic population scenario for the full-scale Waffle.

Pessimistic Growth Scenario

The pessimistic growth scenario forecasted population declines for Drayton, Wahpeton, and Moorhead. In Fargo, Grand Forks, and East Grand Forks, population growth was reduced compared to the baseline scenario. In Breckenridge, population was unchanged from the baseline projection (see Appendix C). Overall, population in the study communities in the pessimistic scenario was collectively 14 percent lower than in the baseline scenario. The use of the pessimistic scenario was to demonstrate that less robust population growth can affect the future expected benefits of the Waffle relative to more robust population growth.

The present value of the gross benefits of the Waffle ranged from $593 million with conservative water storage capacities with the half-scale Waffle to $885 million with moderate water storage capacities with the full-scale Waffle (Table 13). An 14 percent decline in population between the main and pessimistic scenarios produced only a 2 to 3 percent decrease in mitigated flood damages. The difference between the three scenarios is partially due to the relative influences of population growth and changes in real property values. Increasing populations within a community were modeled to have a greater influence on the total value of property at risk from flooding than constant or declining populations. Population only accounted for part of the change in overall property values, the other factor was the trend in real (inflation adjusted) property values. The net result was that lower growth in population or, in some communities, population decline, resulted in relatively less change in flood damages than changes of similar magnitude with population growth.

Net Benefits

Results from the appropriate cost and benefit scenarios were combined to evaluate the economic viability of the Waffle. Results of combining costs and benefits are presented in net terms (i.e., costs subtracted from benefits).

Baseline Growth Scenario

Under the baseline population scenario, net benefits of the Waffle were positive across all cost, scale, and water storage situations except one. Within the baseline population scenario, as expected, net benefits across all combinations were highest with the optimistic cost scenario and lowest with the pessimistic cost scenario. In the baseline cost scenario, net benefits with the full-scale Waffle were estimated to range from over $700 million with moderate water storage combined with minimum acreage to about $125 million with conservative water storage combined with maximum acreage (Table 14). When costs were reduced in the optimistic cost scenario, net benefits were estimated to range from about $760 million with moderate water storage combined with minimum acreage to nearly $266 million with conservative water storage combined with maximum acreage. An increase in costs found with the pessimistic cost scenario produced net benefits which ranged from $627 million with moderate water storage combined with minimum acreage to nearly -$70 million with conservative water storage combined with maximum acreage (Table 14).

With the full-scale Waffle, net benefits from moderate water storage scenarios ranged from 50 percent up to 200 percent greater than net benefits associated with conservative water storage capacities (Table 14). Net benefits for the full-scale Waffle for both moderate and conservative water storage capacities increased by 50 to over 250 percent between the minimum acreage and maximum acreage cost scenarios. Substantial changes in the magnitude of net benefits were observed between combinations of water storage capacities and acreage scenarios, both within and between Waffle scales.

In the baseline cost scenario, net benefits with the half-scale Waffle were estimated to range from over $700 million with moderate water storage combined with minimum acreage to about $330 million with conservative water storage combined with maximum acreage (Table 14). Most patterns of the relative level of net benefits for the half-scale Waffle within the cost scenarios were similar to those observed with the full-scale Waffle. However, the half-scale Waffle with moderate water storage had higher net benefits than the full-scale Waffle with moderate water storage in seven of the nine cost scenarios. The half-scale Waffle had slightly higher net benefits than the full-scale Waffle in the moderate and maximum acreage combinations across the baseline, optimistic, and pessimistic cost scenarios for moderate water storage (Table 14). The same pattern of increased net benefits across all cost scenarios occurred between the half-scale and full-scale Waffle with conservative water storage assumptions.

The difference in net benefits between conservative and moderate water storage with the half-scale Waffle appeared to be generally less than the differences associated with the full-scale Waffle. Also, the degree of increase in net benefits for the half-scale Waffle for both moderate and conservative water storage capacities between the minimum acreage and maximum acreage cost scenarios were less than those found with the full-scale Waffle.

Table 14. Net Benefits of the Waffle, Baseline Population Scenario, 2006 through 2055

	Full-scale Waffle		Half-scale Waffle	
Cost and Acreage Scenarios	Moderate Water Storage	Conservative Water Storage	Moderate Water Storage	Conservative Water Storage
	-- 000s $	--		
Baseline Cost Scenario				
Minimum Acreage	706,859	460,295	703,665	497,590
Moderate Acreage	552,599	306,035	626,832	420,757
Maximum Acreage	371,750	125,186	536,124	330,049
Optimistic Cost Scenario				
Minimum Acreage	759,051	512,487	730,714	524,639
Moderate Acreage	645,253	398,689	674,051	467,976
Maximum Acreage	512,069	265,505	607,243	401,168
Pessimistic Cost Scenario				
Minimum Acreage	627,464	380,900	662,135	456,060
Moderate Acreage	419,918	173,354	558,732	352,657
Maximum Acreage	176,188	(70,376)	436,497	230,422

Optimistic and Pessimistic Growth Scenarios

The optimistic population scenario served to provide an estimate for increased benefits (i.e., relative to baseline population) from the Waffle due to a greater increase in the region’s future population. The pessimistic population scenario served to provide an estimate of reduced benefits (i.e., relative to baseline population) from the Waffle associated with a lower rate of increase in the region’s future population. The lower rate of growth in future population reduced the relative amount of aggregate value of property at risk of flooding.

As was expected, net benefits were greatest across all cost, scale, and water storage combinations with the optimistic population scenario (Table 15). Since all but one combination of factors produced positive net benefits in the baseline scenario, it would be expected that an increase in gross benefits associated with the optimistic population scenario would produce an increase in net benefits. Similarly, net benefits were lowest for each cost, scale, and water storage combination with the pessimistic population scenario (Table 15). Several combinations were estimated to generate net benefits in excess of $800 million under the optimistic population scenario, while the highest net benefits in the pessimistic population scenario were about $700 to $730 million (Table 16).

Table 15. Net Benefits of the Waffle, Optimistic Population Scenario, 2006 through 2055

	Full-scale Waffle		Half-scale Waffle	
Cost and Acreage Scenarios	Moderate Water Storage	Conservative Water Storage	Moderate Water Storage	Conservative Water Storage
	000s $			
Baseline Cost Scenario				
Minimum Acreage	812,930	544,915	799,936	576,345
Moderate Acreage	658,670	390,655	723,103	499,512
Maximum Acreage	477,821	209,806	632,395	408,804
Optimistic Cost Scenario				
Minimum Acreage	865,122	597,107	826,985	603,394
Moderate Acreage	751,324	483,309	770,322	546,731
Maximum Acreage	618,140	350,125	703,514	479,923
Pessimistic Cost Scenario				
Minimum Acreage	733,535	465,520	758,406	534,815
Moderate Acreage	525,989	257,974	655,003	431,412
Maximum Acreage	282,259	14,244	532,768	309,117

As was found in the baseline population scenario, net benefits with moderate and maximum acreage scenarios were generally greater with the half-scale Waffle than with the full-scale Waffle, regardless of water storage assumptions. For example, comparing the conservative water storage scenarios with the full-scale and half-scale Waffle shows that the half-scale Waffle has higher net benefits in all cost scenarios. Across the baseline, optimistic, and pessimistic cost scenarios, substantial difference in net returns could be seen in both the full-scale and half-scale Waffle options when comparing net returns between minimum and maximum acreage assumptions for both the optimistic and pessimistic population scenarios (Tables 15 and 16).

Table 16. Net Benefits of the Waffle, Pessimistic Population Scenario, 2006 through 2055

Cost and Acreage Scenarios	Full-scale Waffle Moderate Water Storage	Full-scale Waffle Conservative Water Storage	Half-scale Waffle Moderate Water Storage	Half-scale Waffle Conservative Water Storage
	---- 000s $ ----			
Baseline Cost Scenario				
Minimum Acreage	677,088	444,513	678,950	484,965
Moderate Acreage	522,828	290,253	602,117	408,132
Maximum Acreage	341,979	109,404	511,409	317,424
Optimistic Cost Scenario				
Minimum Acreage	729,280	496,705	705,999	512,014
Moderate Acreage	615,482	382,907	649,336	455,351
Maximum Acreage	482,298	249,723	582,528	388,543
Pessimistic Cost Scenario				
Minimum Acreage	597,693	365,118	637,420	443,435
Moderate Acreage	390,147	157,572	534,017	340,032
Maximum Acreage	146,417	(86,158)	411,782	217,797

Alternative Evaluation

The economic feasibility of the Waffle is subject to a host of factors–some of which are addressed in this report while others were beyond the scope of this analysis. The goal of this study was to provide a first assessment of the economic viability of the Waffle knowing that this first assessment would not and could not answer all of the economic questions. The paucity of real, tangible data on the start-up, operational, and administrative characteristics of the Waffle make it problematic to generate additional sensitivity analyses of Waffle costs. A greater understanding of the costs of the Waffle will only occur when the knowledge gaps are filled. A similar limitation exists on how much sensitivity analysis should be performed on the benefits of the Waffle with respect to adjusting future population, property values, and other economic variables. Another consideration is that whole categories of benefits have been excluded, and the benefits that are used in this study are subject to a definition of flood damages set forth by the USACE that do not match real-world effects (i.e., particularly in Fargo/Moorhead) in many flood-event sizes.

Given that additional analyses involving changes to hypothetical costs and additional population forecasts would not likely improve the understanding of the economic feasibility of the Waffle, two changes to the baseline conditions were considered: 1) the Waffle was modeled to only be used with low-frequency flood events and 2) the FSDF for Fargo/Moorhead was adjusted to reflect accepted flood protection through a 100-year event, thereby, putting flood susceptibility of Fargo/Moorhead and Drayton at a level that more closely matches protections found in Grand Forks/East Grand Forks and Wahpeton/Breckenridge.

In both of the following analyses, costs of the Waffle were based on baseline assumptions, with the trigger level for using the Waffle set at the 101-year level. All other input variables and parameters associated with costs of operating the Waffle remained unchanged. The costs will not change with either analysis; however, the level of benefits will change. The reason for the change in gross benefits is that the elimination of damages in Fargo/Moorhead at or below the 100-year event has methodological implications based on the integration of flood frequencies and the anticipated difference between with and without flood damages. When the Waffle is only used for low flood frequencies, damages below the 100-year event frequency would cancel out (i.e., same level of damages with and without the Waffle) when the FSDF is not modified. When the FSDF is modified by putting damages to zero below at or below the 100-year event, the difference between damages with and without the Waffle changes considerably, as the crest heights for floods over the 100-year event size are lowered to less than the 100-year event size; the damages at those elevations are zero, and hence the Waffle is calculated to mitigate the entire level of damage at that elevation. This treatment of damages does not occur when only the frequency of Waffle use is modified (e.g., conditions in the other alternative).

Large Flood Events Only Scenario

Operationally, landowner payments for water storage represent a major component of Waffle costs, especially when using an 11-year flood frequency for water storage (Note: the 11-year flood frequency corresponds to data for the flood event size associated with 50 percent of the 1997 flood–the smallest flood event modeled by the EERC-see Table 11). Operating the Waffle at those flood frequencies definitely increases costs and produces few flood-related benefits. In Grand Forks/East Grand Forks and Wahpeton/Breckenridge, improvements in structural flood protections act to eliminate any mitigated flood damages associated with flood events less than the 1997 flood (i.e., flood damages are zero at elevations below 1997 flood crest heights). Most of the communities in the Red River Valley have reasonable protections for high-frequency (low impact) floods, regardless of the flood damages defined by the USACE in their FSDFs. For example, the flood in the spring of 2006 was particularly large, but actual damages throughout the basin were relatively minor. In the case of Fargo/Moorhead, the FSDF for the cities suggested that the area should have incurred $112 million in flood damages, which clearly did not occur. Fargo/Moorhead incurred some expense building temporary dikes and sandbag levies, but received very little actual flood damage. Why incur substantial expenses to provide redundant flood protection?

The alternative analysis assumed the Waffle was only used for flood events larger than the 100-year frequency.

The costs of operating the Waffle only for flood events larger than the 100-year frequency decreased compared to the baseline analysis due to a reduction in total landowner payments (see Appendix E). When landowner payments are made only when water is stored, it would be anticipated, all things equal, that costs would decrease when the Waffle was used less frequently. Costs of operating the full-scale and half-scale Waffle decreased by 28 to 39 percent, when compared to baseline analyses, based on the minimum and maximum acreage scenarios, respectively. For the maximum acreage scenario with full-scale Waffle, costs in the alternative analysis were estimated at $331 million compared to $543 million in the baseline analysis (Table 17).

Net benefits in this alternative scenario were generally lower in magnitude to the baseline analysis across all combinations of acreage, scale, and water storage assumptions (Table 17). Both gross benefits and costs decreased compared to the baseline analysis, which was expected since the Waffle was scheduled to be used less frequently than in the baseline analysis. The difference between net returns in the two analyses suggests that the economics of the Waffle are influenced to some extent by the treatment of how often the Waffle is used. However, nearly all of the benefits within the model that accrue from high-frequency (low impact) floods come from the FSDF for Fargo/Moorhead. When the changes in gross benefits and costs are evaluated, the economics of the Waffle remained substantially positive despite limiting the use of the Waffle to only mitigating low-frequency (high impact) flood events. It would appear that the Waffle would be economical if it was only used to mitigate low-frequency, high impact floods.

Table 17. Gross Benefits, Costs, and Net Benefits of the Waffle from Large Flood Events Only, Baseline Population, 2006 through 2055

	Full-scale Waffle		Half-scale Waffle	
Results	Moderate Water Storage	Conservative Water Storage	Moderate Water Storage	Conservative Water Storage
Alternative Analysis	-- 000s $		--------------------------------------	
Gross Benefits	659,371	426,250	558,858	370,541
Costs				
Minimum Acreage	147,154	147,154	77,441	77,441
Moderate Acreage	231,637	231,637	119,520	119,520
Maximum Acreage	330,666	330,666	169,190	169,190
Net Benefits				
Minimum Acreage	512,217	279,096	481,417	293,100
Moderate Acreage	427,734	194,613	439,338	251,021
Maximum Acreage	328,705	95,584	389,668	201,351
Baseline Analysis	------ results from baseline analysis provided for comparison------			
Gross Benefits	914,790	668,226	811,629	605,554
Costs				
Minimum Acreage	207,931	207,931	107,964	107,964
Moderate Acreage	362,191	362,191	184,797	184,797
Maximum Acreage	543,040	543,040	275,505	275,505
Net Benefits				
Minimum Acreage	706,859	460,295	703,665	497,590
Moderate Acreage	552,599	306,035	626,832	420,757
Maximum Acreage	371,750	125,186	536,124	330,049

Notes: Only flood-events larger than 100-year frequency were modeled.

Modified Fargo/Moorhead Scenario

This alternative analysis focused. primarily on the treatment of potential mitigated flood damages in Fargo/Moorhead and Drayton, but also included changes in the frequency of use for the Waffle. This alternative analysis eliminates the flood damages for 100-year or smaller floods in Fargo/Moorhead. The elimination of damages at those elevations reflects more closely real world events and anticipates some of the changes that would occur to the

FSDF if the metro area implemented additional permanent flood protections. Also, it more closely reflects the expected level of damages in the other metro areas in the Valley. For consistency, Drayton was also assumed to be flood-proof to the 100-year level.

The FSDF for Fargo/Moorhead indicates that substantial damages begin occurring in the two cities with modest elevations in the Red River. For example in 2006, according to the FSDF for Fargo/Moohead, at an elevation of 895 feet msl which equates to about a 22-year event, damages would be about \$3.6 million. While some damages occur at relatively low river heights due to inundation of park areas, golf courses, and other relatively unprotected areas, local flood fighting efforts in combination with permanent protections act to eliminate most damages to residential and commercial structures for high-frequency flood events. As stated before, the FSDF represents damages that would likely occur in the absence of local flood fighting provisions (i.e., temporary dikes, sandbagging). It is difficult to reconcile the level of damages suggested by the FSDF for higher frequency floods in the two cities with the level of damages that actually occur. Another example can be drawn from the spring 2006 flood. The Red River in Fargo/Moorhead reached a crest of 899 msl, which according to the FSDF should have produced about \$112 million in damages.

Despite that the Fargo/Moorhead area does not have a large-scale structural flood protection project similar to those in the finishing stages in Grand Forks/East Grand Forks and Wahpeton/Breckenridge, Fargo/Moorhead has repeatedly, to date, used a combination of temporary and permanent flood fighting measures to prevent widespread flood damage. It would be safe to assume that those efforts will continue to be successful in the future with flood-events of similar size (e.g., 1997, 2006).

Fargo/Moorhead continues to pursue additional flood protection provisions for parts of the two cities. It is possible that structural protections will be implemented in the near future changing the FSDF for the two cities. Permanent, structural flood protection is already underway in Oak Port Township as properties are being acquired to begin construction of a dike in that area. Also, plans to implement permanent flood protection continue to be debated for regions of south Fargo (Nowatzki 2007a). Spring flooding in June of 2007 renewed debates on a permanent downtown dike for Fargo (Nowatzki 2007b).

Much of the damages in the FSDF for Fargo/Moorhead are a function of definition in that they result from no local flood fighting provisions and begin occurring with high-frequency floods. However, damages predicted in the FSDFs for very large flood events are less sensitive to those assumptions and represent a stronger correlation between flood size and real damages since the river crest heights for those events exceed, in most cases, the capacities of existing permanent structural flood protections. Also, at these extreme flood crest heights, the reliability of temporary provisions for flood mitigation becomes tenuous. It is of greater value to focus solely on the mitigated flood damages from large floods, since

Fargo/Moorhead, for various reasons, appears to consistently eliminate damages from lesser floods.

The final reason for adjusting the FSDF for Fargo/Moorhead is to reduce the mitigated flood damages from Fargo/Moorhead and evaluate how those reductions influence the economic feasibility of the Waffle. The pool of benefits from Fargo/Moorhead, given the current FSDF, completely dominates the economic feasibility of the Waffle. The percentage of all benefits arising from mitigated damages in Fargo/Moorhead under the moderate water storage scenarios represent 79 percent to 84 percent of all benefits (Appendix G). The percentage of damages coming from Fargo/Moorhead increase under the conservative water storage scenarios and range from 93 to 97 percent of total benefits (Appendix G). When the Waffle is predicted to have less influence reducing the effects of large floods, the potential to mitigate damage in the other cities decreases. Since the FSDF for Fargo/Moorhead implies the cities are vulnerable to small and medium flood events, the relative share of mitigated damages from Fargo/Moorhead increase. Given the absence of other benefits in the analysis (e.g., environmental, rural infrastructure, small communities), the economic feasibility of the Waffle to this point has been solely determined by how much damages are derived from Fargo/Moorhead.

Net benefits in this alternative scenario were similar in magnitude to the baseline analysis (Table 18). Both gross benefits and costs decreased compared to the baseline analysis, which was expected since the FSDF for Fargo/Moorhead was adjusted and the Waffle was scheduled to be used less frequently than in the baseline analysis. In this alternative, gross benefits decreased slightly more than costs in the minimum acreage scenarios, which resulted in lower net benefits compared to the baseline analysis (Table 18). However, in most of the moderate and maximum acreage scenarios, costs decreased slightly more than gross benefits resulting in higher net benefits compared to the baseline analysis. Overall, net benefits ranged from $674 million to $255 million, depending upon acreage, scale, and water storage assumptions (Table 18). While numerically some combinations of acreage, scale, and water storage capacities produced greater net returns under the assumptions used in this alternative when compared to the baseline analysis, the difference between net returns in the two analyses suggests that the economics of the Waffle are not overly sensitive to the inclusion or absence of high-frequency flood damages within the FSDF for Fargo/Moorhead.

Table 18. Gross Benefits, Costs, and Net Benefits of the Waffle, Modified Damages in Fargo/Moorhead and Drayton, Baseline Population, 2006 through 2055

	Full-scale Waffle		Half-scale Waffle	
Results	Moderate Water Storage	Conservative Water Storage	Moderate Water Storage	Conservative Water Storage
<u>Alternative Analysis</u>	--------------------------------------- 000s $ ---------------------------------------			
Gross Benefits	821,223	585,910	731,318	533,564
Costs				
Minimum Acreage	147,154	147,154	77,441	77,441
Moderate Acreage	231,637	231,637	119,520	119,520
Maximum Acreage	330,666	330,666	169,190	169,190
Net Benefits				
Minimum Acreage	674,069	438,756	653,877	456,123
Moderate Acreage	589,586	354,273	611,798	414,044
Maximum Acreage	490,557	255,244	562,128	364,374
<u>Baseline Analysis</u>	------- results from baseline analysis provided for comparison-------			
Gross Benefits	914,790	668,226	811,629	605,554
Costs				
Minimum Acreage	207,931	207,931	107,964	107,964
Moderate Acreage	362,191	362,191	184,797	184,797
Maximum Acreage	543,040	543,040	275,505	275,505
Net Benefits				
Minimum Acreage	706,859	460,295	703,665	497,590
Moderate Acreage	552,599	306,035	626,832	420,757
Maximum Acreage	371,750	125,186	536,124	330,049

Notes: Only flood-events larger than 100-year frequency were modeled. Damages in the FSDF for Fargo/Moorhead and Drayton were set to zero for elevations at or below the 100-year flood event.

SUMMARY AND CONCLUSIONS

The Waffle appears to be cost-effective at mitigating economic damages associated with large flood events, given the current knowledge about its operational characteristics and physical effects on crest heights in the Basin. Due primarily to a lack of certainty or confidence on various economic aspects of the Waffle, a plausible range of costs was evaluated and combined with a range of mitigated flood benefits from four urban areas in the Basin. However, despite substantially large net benefits, variations in acreage and water storage assumptions produced rather large swings in the magnitude of those net benefits. The analysis was extremely conservative by only including a potential sub-set of the likely benefits of the Waffle. The inclusion of basin-wide environmental benefits and flood damage mitigation in small communities and rural areas would only increase the economic attractiveness of the Waffle.

Despite that the Waffle appears to be economical over a wide range of possibilities, a number of uncertainties warrant further investigation. The costs of implementing the Waffle are unknown. Landowner willingness to participate throughout the Basin is unknown. How would temporarily storing water affect farm program payments and insurable crop yields? Would landowners enroll sufficient land in the Waffle at the payment levels used in the analysis? Answers to these and other cost-related factors, in addition to other operational issues, are not yet available. As a result, a range of costs were used, but most of those expenses still represent best guesses at this point.

What is the economically optimal scale of the Waffle? Two-scale options, a full-scale and a half-scale Waffle, were used. The basis for the scale options was due to uncertainty on landowner participation. Within each scale, three acreage possibilities were considered. Again, three acreage options were required to cover the uncertainty pertaining to payment acreage associated with flooded acreage. The point is that data on two critical physical measures of the Waffle – payment acreage (minimum, moderate, and maximum acreage scenarios) and landowner enrollment (full- and half-scale scenarios) – remain estimates that have not been calibrated from township- or watershed-level ground observations. The implication is that the economics appeared to show diminishing net returns between the half- and full-scale Waffle. These results suggest further analysis should be conducted to determine the optimal scale of the Waffle; however, uncertainty on payment acreage and landowner enrollment makes estimating optimal Waffle size problematic.

The results of this study also generate questions on targeting land enrollment to protect selected areas and raise concerns over the geographic scope of Waffle implementation. For example, the economics of the Waffle were almost entirely determined by what happens in Fargo/Moorhead. In nearly all scenarios, the Waffle would be economical if only benefits from Fargo/Moohead were included. Without Fargo/Moorhead, the Waffle would not be economical except under a limited number of conditions, given the breadth of benefits in this study. For the remainder of the basin, could Waffle enrollment be targeted on a smaller scale to more closely match costs and benefits? A substantial amount of acreage in counties in the northern third of the Basin were included in the analysis. Should enrollment (and hence cost estimates) in those counties be more closely matched to localized benefits? What level of economic criteria should be used to justify enrollment in the Waffle? Clearly, acreage next to the Canadian border is likely to produce few benefits in the U.S. portion of the Basin. It is possible that targeting enrollment in the southern Red River Valley would provide most of the Waffle benefits at a fraction of the cost of even the half-scale scenario.

This first assessment of the Waffle limited benefits to mitigated flood damages from four urban areas. A number of other mitigated flood damages could also be evaluated. The Waffle's effect on mitigating flood damage to rural infrastructure, farmsteads, smaller communities, and commerce is largely unknown. Would the Waffle's effects on lower crest heights also reduce damages to those rural properties? What mitigation of damages from overland flooding could the Waffle generate? How much mitigated flood damage would be generated in the Canadian side of the Red River Basin?

No attempt was made to model environmental benefits associated with the Waffle. It is a foregone conclusion that including environmental benefits at this point would add to the economic attractiveness of the Waffle. However, would the location or generation of environmental benefits be sufficient to change the scale or influence the targeting of land enrollment in the Waffle? Would some environmental benefits accrue to land enrolled in the Waffle? If so, those benefits need to be documented and quantified to be of value to landowners when making decisions on enrollment. If the Waffle reduces the flow of sediment, fertilizers, and other pollutants into Lake Winnipeg, what implications would that have on financial support for the Waffle from Canadian authorities? A host of operational and economic issues remain unanswered on the environmental aspects of the Waffle.

Flood risk imposes real costs on property owners. Some of these costs are cash, such as added insurance premiums; other costs are non-cash, such as depressed property values. If flood risks decrease, both cash and non-cash costs are reduced. However, this study did not consider the benefits associated with these mitigated costs. It is also reasonable to expect that reduced flood risk, in some locations, will spur economic development. In areas that have received flood protection measures, anecdotal evidence suggests that residential and commercial development has followed as a result of that flood protection. Economic theory supports this argument. If the costs of developing and owning real property decrease, the value of development increases. So, more development results from increased flood protection. Again, this study's assessment does not account for these potential economic benefits.

The issue of who pays for flood protection generated by the Waffle merits consideration. Currently, the costs for structural flood protection are paid for with a mix of federal, state, and local funding with the U.S. Army Corps of Engineers having responsibility for designing, constructing, and monitoring flood mitigation structures. Which federal program(s) would contribute financially to a non-structural flood protection project such as the Waffle? Would new federal legislation be required to obtain federal funds? How would federal use of National Economic Development (NED) planning criteria change the level of net economic benefits? It would seem that a potential obstacle to implementing the Waffle basin wide could be financial feasibility. Regardless of the level of net benefits, the costs of operating the Waffle basin wide would require, at a minimum, several hundred million dollars over the next half century. While the benefits would be represented by mitigated flood damages and non-market environmental benefits, operating the Waffle would require real funds and/or dedicated financial support. Evaluation of economic feasibility is one issue; however, it is another separate issue to obtain the funds to operate the Waffle on a basin wide scale.

Despite an extremely conservative approach to estimating the net benefits of the Waffle, the Waffle appears to be capable of generating around \$200 million to \$600 million in net benefits over a 50-year period. While these initial results are substantial, policymakers are still likely to be concerned about the number of issues, questions, and obstacles that remain unanswered. The positive results from this study suggest that dedicating additional resources to solving many of the remaining issues with the Waffle would be justified. Perhaps additional resources could be used to implement a pilot version of the Waffle, albeit at a watershed or township level, to more fully understand the operational characteristics of the Waffle. Information from a pilot study would provide most of the necessary information to refine economic analyses, and provide the groundwork for more widespread implementation.

REFERENCES

Bolles, Bethany A., Xixi Wang, Barry W. Botnen, Douglas R. Davidson, Lynette L. de Silva, Sheila Hanson, Marc D. Kurz, Andrew P. Manale, Wesley D. Peck, Edward N. Steadman, and Kirk D. Williams. 2004. *An Innovative Approach to Basinwide Flood Control: The Evaluation of the Waffle℠ Concept*. Progress Report: April, 2002 through January 2004. Energy & Environmental Research Center, University of North Dakota, Grand Forks.

Bureau of Reclamation. 2005. *Report on Red River Valley Water Supply Project Needs and Options: Current and Future Population of the Red River Valley Region 2000 through 2050*. Final Report. U.S. Department of Interior, Bureau of Reclamation, Great Plains Region, Dakotas Area Office, Bismarck, ND.

Energy & Environmental Research Center. 2007. Unpublished data. Energy & Environmental Research Center, University of North Dakota, Grand Forks.

Hachfeld, Gary, William Lazarus, and Dale Nordquist. 2005. *Cropland Rental Rates for Minnesota Counties*. University of Minnesota Extension Service, University of Minnesota, St. Paul.

International Joint Commission. 1997. *Red River Flooding: Short-term Measures*. Interim Report of the International Red River Basin Task Force to the International Joint Commission. International Joint Commission, Ottawa, Ontario, Canada and Washington, D.C., U.S.A.

International Joint Commission. 2000. *Living with the Red.* Report to the Governments of Canada and the United States on Reducing Flood Impacts in the Red River Basin. International Joint Commission, Ottawa, Ontario, Canada and Washington, D.C., U.S.A.

Kurz, B.A., E.N. Steadman, J.A. Harju, X. Wang, L.L. de Silva, S.K. Hanson, M.D. Kurz, W.D. Peck, and T.K. Simonsen. 2007. *An Evaluation of Basinwide, Distributed Storage in the Red River Basin–the Waffle Concept*. Final Report for U.S. Department of Agriculture, Natural Resources Conservation Service, Grant Agreement No. 69-6633-2-4. Energy & Environmental Research Center, University of North Dakota, Grand Forks.

Minnesota State Demographic Center. 2002. *Minnesota Population Projections 2000-2030.* Minnesota State Demographic Center, St. Paul, MN.

National Agricultural Statistics Service. 2004. *2002 Census of Agriculture*. North Dakota: Volume 1, Geographic Area Series Part 34. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C.

National Agricultural Statistics Service. 2005a. *North Dakota 2005 County Rents & Values*. North Dakota Agricultural Statistics Service, National Agricultural Statistics Service, U.S. Department of Agriculture, Fargo, ND.

National Agricultural Statistics Service. 2005b. *South Dakota 2005 County Level Land Rents and Values*. South Dakota Agricultural Statistics Service, National Agricultural Statistics Service, U.S. Department of Agriculture Sioux Falls, SD.

Northwest Economic Associates. 2003. *Population Projections for Red River Valley Counties and Municipalities, 2000 through 2050.* Northwest Economic Associates, Vancouver, WA.

Nowatzki, Mike. 2007a. "Flood Protection Faces Barrier." *The Forum*, May 15.

Nowatzki, Mike. 2007b. "Walaker: Cost Big Hurdle for Downtown Flood Wall." *The Forum*, June 6.

Office of Federal Housing Enterprise Oversight. 2006. *House Price Index*. http://www.ofheo.gov/HPI.asp Office of Housing Enterprise Oversight, Washington, D.C.

Shultz, S.D. and J.A. Leitch. 2003. "The Feasibility of Restoring Previously Drained Wetlands to Reduce Flood Damage." *Journal of Soil and Water Conservation* 58(1):21-29.

U.S. Army Corps of Engineers. 1997. *Feasibility Report and Environmental Assessment Crookston, MN*. Appendix B. U.S. Army Corps of Engineers, St. Paul, MN.

U.S. Army Corps of Engineers. 1998. *General Reevaluation Report and Environmental Impact Statement. East Grand Forks, MN and Grand Forks, ND*. Volume 1, Supplementary Documentation Appendix C, Economic Analysis. U.S. Army Corps of Engineers, St. Paul, MN.

U.S. Army Corps of Engineers. 2000a. *Feasibility Study and Environmental Assessment Breckenridge, MN Section 205 Local Flood Reduction Project Red River of the North*. Appendix C. U.S. Army Corps of Engineers, St. Paul, MN.

U.S. Army Corps of Engineers. 2000b. *Feasibility Study and Environmental Assessment, Wahpeton, ND, Section 205 Local Flood Reduction Project, Red River of the North*. Appendix C. U.S. Army Corps of Engineers, St. Paul, MN.

U.S. Army Corps of Engineers. 2003. *General Reevaluation Report: Grafton, ND*. Appendix E. U.S. Army Corps of Engineers, St. Paul, MN.

U.S. Army Corps of Engineers. 2004. *Economic Analysis, Section 205, Drayton, ND*. Letter Report. U.S. Army Corps of Engineers, St. Paul, MN.

U.S. Army Corps of Engineers. 2005. *Fargo-Moorhead and Upstream Feasibility Study: Preliminary Phase I Summary*. U.S. Army Corps of Engineers, St. Paul, MN.

U.S. Army Corps of Engineers. 2006. Personal communication. U.S. Army Corps of Engineers, St. Paul, MN.

U.S. Department of Agriculture. 1997. *Agricultural Prices: 1996 Summary*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C.

U.S. Department of Agriculture. 2005. *Agricultural Prices: 2004 Summary*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C.

U.S. Department of Commerce. 2006. *Implicit Price Deflators for Gross Domestic Product*. http://www.bea.gov/national/index.htm#gdp , Bureau of Economic Analysis, U.S. Department of Commerce, Washington, D.C.

U.S. Department of Labor. 2006. *Consumer Price Index*. http://www.bls.gov/cpi/ Bureau of Labor Statistics, U.S. Department of Labor, Washington, D.C.

APPENDIX A

Estimated Payment Acreage and Sections of Land, by Land Type, Relief Category, County, State, and Waffle Scale

Appendix Table A1. Estimated Payment Acreage for Full-scale and Half-scale Waffle, by Land Type, Relief Contour, County, and State

State/County	Land Type	Relief Contour	Half-scale Waffle Minimum	Half-scale Waffle Moderate	Half-scale Waffle Maximum	Full-scale Waffle Minimum	Full-scale Waffle Moderate	Full-scale Waffle Maximum
North Dakota								
Barnes	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	117	352	587	294	881	1,468
		4 - 10	3,112	6,224	7,780	6,224	12,449	15,561
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	11	32	53	26	79	132
		4 - 10	280	560	700	560	1,119	1,399
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	64	128	160	64	128	160
Benson	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	373	746	933	693	1,386	1,732
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	75	150	187	139	278	348
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
Cass	Cropland	0 - 2	5,484	8,774	16,451	11,281	18,049	33,842
		2 - 4	3,760	11,281	18,801	8,586	25,758	42,929
		4 - 10	6,518	13,036	16,294	13,161	26,322	32,902
	Pasture	0 - 2	116	186	349	239	383	718
		2 - 4	80	239	399	182	546	911
		4 - 10	138	276	346	279	558	698
	Other Land	0 - 2	160	256	480	320	512	960
		2 - 4	64	192	320	64	192	320
		4 - 10	0	0	0	0	0	0
Cavalier	Cropland	0 - 2	0	0	0	157	252	472
		2 - 4	1,195	3,586	5,976	2,013	6,039	10,065
		4 - 10	4,970	9,939	12,424	9,751	19,501	24,377
	Pasture	0 - 2	0	0	0	3	4	8
		2 - 4	85	254	424	163	489	815
		4 - 10	86	173	216	169	339	423
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	64	192	320	64	192	320
		4 - 10	128	256	320	320	640	800
Eddy	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	200	600	1,000	350	1,050	1,751
		4 - 10	0	0	0	0	0	0
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	56	168	280	98	294	489
		4 - 10	0	0	0	0	0	0

Appendix Table A1. Continued

State/County	Land Type	Relief Contour	Half-scale Waffle Minimum	Half-scale Waffle Moderate	Half-scale Waffle Maximum	Full-scale Waffle Minimum	Full-scale Waffle Moderate	Full-scale Waffle Maximum
North Dakota								
Eddy-cont.	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
Foster	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	55	166	277	111	332	554
		4 - 10	0	0	0	0	0	0
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	9	26	43	81	244	406
		4 - 10	0	0	0	0	0	0
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
Grand Forks	Cropland	0 - 2	4,823	7,717	14,470	8,402	13,443	25,205
		2 - 4	2,801	8,402	14,003	5,601	16,804	28,006
		4 - 10	2,738	5,477	6,846	5,663	11,327	14,159
	Pasture	0 - 2	137	219	410	238	381	715
		2 - 4	143	430	717	223	668	1,114
		4 - 10	270	539	674	417	833	1,041
	Other Land	0 - 2	160	256	480	160	256	480
		2 - 4	0	0	0	64	192	320
		4 - 10	0	0	0	128	256	320
Griggs	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	392	1,177	1,962	897	2,691	4,485
		4 - 10	0	0	0	0	0	0
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	56	167	278	127	381	635
		4 - 10	0	0	0	0	0	0
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
McHenry	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	173	346	433	346	693	866
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	275	550	687	358	715	894
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	64	128	160	128	256	320
Nelson	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	58	173	289	173	519	866
		4 - 10	808	1,616	2,020	1,789	3,578	4,472
	Pasture	0 - 2	0	0	0	0	0	0

Appendix Table A1. Continued

		Relief	Half-scale Waffle			Full-scale Waffle		
State/County	Land Type	Contour	Minimum	Moderate	Maximum	Minimum	Moderate	Maximum
North Dakota								
Nelson-cont.	Pasture	2 - 4	6	19	31	19	57	94
		4 - 10	88	176	220	195	390	488
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	64	128	160	128	256	320
Pembina	Cropland	0 - 2	3,765	6,025	11,296	7,688	12,300	23,063
		2 - 4	3,891	11,673	19,455	7,719	23,157	38,596
		4 - 10	1,883	3,765	4,707	3,640	7,280	9,100
	Pasture	0 - 2	235	375	704	312	500	937
		2 - 4	141	423	705	345	1,035	1,724
		4 - 10	37	75	93	72	144	180
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
Pierce	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	582	1,164	1,455	1,217	2,434	3,043
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	122	244	305	383	766	957
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
Ransom	Cropland	0 - 2	0	0	0	122	195	367
		2 - 4	0	0	0	0	0	0
		4 - 10	1,515	3,030	3,787	3,079	6,158	7,697
	Pasture	0 - 2	0	0	0	38	61	113
		2 - 4	0	0	0	0	0	0
		4 - 10	981	1,962	2,453	1,657	3,314	4,143
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
Richland	Cropland	0 - 2	6,390	10,224	19,170	13,997	22,395	41,991
		2 - 4	3,104	9,311	15,518	6,025	18,074	30,124
		4 - 10	3,043	6,086	7,607	6,572	13,145	16,431
	Pasture	0 - 2	330	528	990	723	1,157	2,169
		2 - 4	224	673	1,122	375	1,126	1,876
		4 - 10	349	698	873	852	1,703	2,129
	Other Land	0 - 2	0	0	0	480	768	1,440
		2 - 4	64	192	320	256	768	1,280
		4 - 10	256	512	640	320	640	800
Rolette	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0

Appendix Table A1. Continued

State/County	Land Type	Relief Contour	Half-scale Waffle Minimum	Half-scale Waffle Moderate	Half-scale Waffle Maximum	Full-scale Waffle Minimum	Full-scale Waffle Moderate	Full-scale Waffle Maximum
North Dakota								
Rolette-cont.	Cropland	4 - 10	54	108	135	108	216	270
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	10	20	25	20	40	50
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
Sargent	Cropland	0 - 2	0	0	0	145	232	435
		2 - 4	522	1,567	2,612	1,451	4,353	7,254
		4 - 10	3,598	7,196	8,996	7,022	14,045	17,556
	Pasture	0 - 2	0	0	0	15	24	45
		2 - 4	54	161	268	149	447	746
		4 - 10	370	740	924	722	1,443	1,804
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	128	384	640	128	384	640
		4 - 10	128	256	320	192	384	480
Sheridan	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	432	864	1,080	816	1,633	2,041
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	208	416	520	336	671	839
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	64	128	160	64	128	160
Steele	Cropland	0 - 2	0	0	0	153	244	458
		2 - 4	489	1,466	2,444	855	2,566	4,277
		4 - 10	1,466	2,933	3,666	2,872	5,744	7,180
	Pasture	0 - 2	0	0	0	7	12	22
		2 - 4	23	70	116	41	122	203
		4 - 10	70	139	174	136	272	340
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	128	256	320	128	256	320
Towner	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	61	184	307
		4 - 10	491	982	1,228	921	1,842	2,302
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	3	8	13
		4 - 10	85	170	212	103	206	258
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	64	128	160

Appendix Table A1. Continued

		Relief	Half-scale Waffle			Full-scale Waffle		
State/County	Land Type	Contour	Minimum	Moderate	Maximum	Minimum	Moderate	Maximum
North Dakota								
Traill	Cropland	0 - 2	5,864	9,382	17,591	10,776	17,242	32,329
		2 - 4	3,486	10,459	17,432	6,402	19,207	32,012
		4 - 10	2,789	5,578	6,973	5,452	10,903	13,629
	Pasture	0 - 2	56	90	169	104	166	311
		2 - 4	34	101	168	62	185	308
		4 - 10	27	54	67	52	105	131
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	128	384	640	128	384	640
		4 - 10	64	128	160	64	128	160
Walsh	Cropland	0 - 2	3,015	4,823	9,044	5,879	9,406	17,636
		2 - 4	2,050	6,150	10,250	3,738	11,214	18,691
		4 - 10	1,507	3,015	3,768	3,135	6,270	7,838
	Pasture	0 - 2	185	297	556	361	578	1,084
		2 - 4	126	378	630	230	690	1,149
		4 - 10	93	185	232	193	386	482
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	64	192	320
		4 - 10	128	256	320	192	384	480
Wells	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	968	1,936	2,420	1,765	3,530	4,412
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	248	496	620	411	822	1,028
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
Minnesota								
Becker	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	240	720	1,200	300	900	1,500
		4 - 10	780	1,560	1,950	1,680	3,360	4,201
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	16	48	80	20	60	100
		4 - 10	52	104	130	112	224	279
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	64	128	160	64	128	160
Beltrami	Cropland	0 - 2	0	0	0	129	207	388
		2 - 4	104	311	518	207	622	1,036
		4 - 10	0	0	0	0	0	0
	Pasture	0 - 2	0	0	0	31	49	92
		2 - 4	24	73	122	49	146	244
		4 - 10	0	0	0	0	0	0

Appendix Table A1. Continued

State/County	Land Type	Relief Contour	Half-scale Waffle Minimum	Half-scale Waffle Moderate	Half-scale Waffle Maximum	Full-scale Waffle Minimum	Full-scale Waffle Moderate	Full-scale Waffle Maximum
North Dakota								
Beltrami	Other Land	0 - 2	640	1,024	1,920	1,440	2,304	4,320
		2 - 4	832	2,496	4,160	1,536	4,608	7,680
		4 - 10	0	0	0	0	0	0
Big Stone	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	62	185	309	62	185	309
		4 - 10	0	0	0	0	0	0
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	2	7	11	2	7	11
		4 - 10	0	0	0	0	0	0
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
Clay	Cropland	0 - 2	4,924	7,878	14,772	10,002	16,003	30,006
		2 - 4	2,647	7,940	13,233	5,478	16,434	27,390
		4 - 10	677	1,354	1,693	1,600	3,201	4,001
	Pasture	0 - 2	196	314	588	398	637	1,194
		2 - 4	105	316	527	218	654	1,090
		4 - 10	27	54	67	64	127	159
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	64	192	320	128	384	640
		4 - 10	0	0	0	0	0	0
Clearwater	Cropland	0 - 2	257	411	770	513	821	1,540
		2 - 4	257	770	1,283	565	1,694	2,823
		4 - 10	0	0	0	0	0	0
	Pasture	0 - 2	63	101	190	127	203	380
		2 - 4	63	190	317	139	418	697
		4 - 10	0	0	0	0	0	0
	Other Land	0 - 2	1,760	2,816	5,280	3,040	4,864	9,120
		2 - 4	1,024	3,072	5,120	2,240	6,720	11,200
		4 - 10	0	0	0	128	256	320
Grant	Cropland	0 - 2	314	502	941	1,097	1,756	3,292
		2 - 4	1,693	5,080	8,466	2,508	7,525	12,542
		4 - 10	376	753	941	815	1,631	2,038
	Pasture	0 - 2	6	10	19	23	36	68
		2 - 4	35	104	174	52	155	258
		4 - 10	8	15	19	17	33	42
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	64	192	320	64	192	320
		4 - 10	0	0	0	64	128	160
Kittson	Cropland	0 - 2	3,359	5,375	10,078	6,414	10,262	19,241
		2 - 4	2,199	6,597	10,995	5,253	15,759	26,265
		4 - 10	1,405	2,810	3,512	2,871	5,742	7,177
	Pasture	0 - 2	161	257	482	306	490	919

Appendix Table A1. Continued

		Relief	Half-scale Waffle			Full-scale Waffle		
State/County	Land Type	Contour	Minimum	Moderate	Maximum	Minimum	Moderate	Maximum
North Dakota								
Kittson-cont	Pasture	2 - 4	105	315	525	251	753	1,255
		4 - 10	67	134	168	137	274	343
	Other Land	0 - 2	2,880	4,608	8,640	6,400	10,240	19,200
		2 - 4	1,728	5,184	8,640	3,200	9,600	16,000
		4 - 10	320	640	800	576	1,152	1,440
Lake of the Woods	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
	Other Land	0 - 2	0	0	0	160	256	480
		2 - 4	64	192	320	64	192	320
		4 - 10	0	0	0	0	0	0
Mahnomen	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	305	915	1,524	549	1,646	2,744
		4 - 10	1,280	2,561	3,201	2,256	4,512	5,640
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	15	45	76	27	82	136
		4 - 10	64	127	159	112	224	280
	Other Land	0 - 2	160	256	480	160	256	480
		2 - 4	128	384	640	256	768	1,280
		4 - 10	192	384	480	448	896	1,120
Marshall	Cropland	0 - 2	5,607	8,971	16,820	9,967	15,948	29,902
		2 - 4	4,797	14,390	23,984	9,843	29,528	49,214
		4 - 10	1,059	2,118	2,648	1,931	3,862	4,828
	Pasture	0 - 2	153	245	460	273	436	818
		2 - 4	131	394	656	269	808	1,346
		4 - 10	29	58	72	53	106	132
	Other Land	0 - 2	1,280	2,048	3,840	3,040	4,864	9,120
		2 - 4	1,152	3,456	5,760	2,304	6,912	11,520
		4 - 10	256	512	640	576	1,152	1,440
Norman	Cropland	0 - 2	3,942	6,307	11,825	8,514	13,623	25,543
		2 - 4	1,955	5,865	9,776	4,162	12,487	20,812
		4 - 10	2,270	4,541	5,676	4,667	9,334	11,668
	Pasture	0 - 2	58	93	175	126	201	377
		2 - 4	29	87	144	62	185	308
		4 - 10	34	67	84	69	138	172
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	192	384	480	192	384	480
Otter Tail	Cropland	0 - 2	0	0	0	0	0	0

Appendix Table A1. Continued

State/County	Land Type	Relief Contour	Half-scale Waffle Minimum	Half-scale Waffle Moderate	Half-scale Waffle Maximum	Full-scale Waffle Minimum	Full-scale Waffle Moderate	Full-scale Waffle Maximum
North Dakota								
Otter Tail	Cropland	2 - 4	0	0	0	59	178	296
		4 - 10	119	237	296	237	474	593
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	5	14	24
		4 - 10	9	19	24	19	38	47
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
Pennington	Cropland	0 - 2	2,754	4,406	8,262	5,508	8,813	16,523
		2 - 4	2,632	7,895	13,158	5,263	15,789	26,315
		4 - 10	122	245	306	184	367	459
	Pasture	0 - 2	126	202	378	252	403	757
		2 - 4	120	361	602	241	723	1,205
		4 - 10	6	11	14	8	17	21
	Other Land	0 - 2	320	512	960	800	1,280	2,400
		2 - 4	192	576	960	384	1,152	1,920
		4 - 10	0	0	0	0	0	0
Polk	Cropland	0 - 2	9,367	14,988	28,102	16,861	26,978	50,583
		2 - 4	4,808	14,425	24,042	9,742	29,226	48,709
		4 - 10	2,061	4,122	5,152	3,997	7,993	9,992
	Pasture	0 - 2	233	372	698	419	670	1,257
		2 - 4	120	359	598	242	726	1,211
		4 - 10	51	102	128	99	199	248
	Other Land	0 - 2	320	512	960	480	768	1,440
		2 - 4	320	960	1,600	512	1,536	2,560
		4 - 10	192	384	480	192	384	480
Red Lake	Cropland	0 - 2	1,081	1,730	3,244	1,854	2,966	5,561
		2 - 4	1,112	3,337	5,561	2,286	6,859	11,431
		4 - 10	0	0	0	0	0	0
	Pasture	0 - 2	39	62	116	66	106	199
		2 - 4	40	119	199	82	245	409
		4 - 10	0	0	0	0	0	0
	Other Land	0 - 2	160	256	480	960	1,536	2,880
		2 - 4	128	384	640	320	960	1,600
		4 - 10	0	0	0	0	0	0
Roseau	Cropland	0 - 2	1,722	2,755	5,166	3,757	6,011	11,271
		2 - 4	1,252	3,757	6,262	2,818	8,453	14,089
		4 - 10	0	0	0	0	0	0
	Pasture	0 - 2	38	61	114	83	133	249
		2 - 4	28	83	138	62	187	311
		4 - 10	0	0	0	0	0	0
	Other Land	0 - 2	1,440	2,304	4,320	2,240	3,584	6,720
		2 - 4	768	2,304	3,840	1,472	4,416	7360

Appendix Table A1. Continued

State/County	Land Type	Relief Contour	Half-scale Waffle Minimum	Half-scale Waffle Moderate	Half-scale Waffle Maximum	Full-scale Waffle Minimum	Full-scale Waffle Moderate	Full-scale Waffle Maximum
North Dakota								
Roseau-cont.	Other Land	4 - 10	0	0	0	64	128	160
Stevens	Cropland	0 - 2	310	496	930	620	992	1,859
		2 - 4	310	930	1,550	1,240	3,719	6,198
		4 - 10	0	0	0	0	0	0
	Pasture	0 - 2	10	16	30	20	32	61
		2 - 4	10	30	50	40	121	202
		4 - 10	0	0	0	0	0	0
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
Traverse	Cropland	0 - 2	4,995	7,991	14,984	8,272	13,236	24,817
		2 - 4	3,122	9,365	15,608	6,181	18,542	30,904
		4 - 10	562	1,124	1,405	1,186	2,372	2,966
	Pasture	0 - 2	125	201	376	208	332	623
		2 - 4	142	427	712	219	658	1,096
		4 - 10	14	28	35	30	60	74
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	64	128	160
Wilkin	Cropland	0 - 2	4,554	7,286	13,662	8,323	13,316	24,968
		2 - 4	3,957	11,871	19,786	8,919	26,758	44,597
		4 - 10	1,005	2,010	2,512	2,198	4,397	5,496
	Pasture	0 - 2	86	138	258	157	252	472
		2 - 4	75	225	374	169	506	843
		4 - 10	19	38	48	42	83	104
	Other Land	0 - 2	160	256	480	160	256	480
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
South Dakota								
Marshall	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	45	136	227	45	136	227
		4 - 10	91	181	227	136	272	340
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	19	56	93	19	56	93
		4 - 10	37	75	93	56	112	140
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	0	0	0
		4 - 10	0	0	0	0	0	0
Roberts	Cropland	0 - 2	0	0	0	0	0	0
		2 - 4	105	314	523	157	471	785
		4 - 10	1,151	2,302	2,877	2,197	4,394	5,493
	Pasture	0 - 2	0	0	0	0	0	0
		2 - 4	23	70	117	35	105	175

Appendix Table A1. Continued

State/County	Land Type	Relief Contour	Half-scale Waffle Minimum	Half-scale Waffle Moderate	Half-scale Waffle Maximum	Full-scale Waffle Minimum	Full-scale Waffle Moderate	Full-scale Waffle Maximum
North Dakota								
Roberts-cont	Pasture	4 - 10	257	514	643	491	982	1,227
	Other Land	0 - 2	0	0	0	0	0	0
		2 - 4	0	0	0	64	192	320
		4 - 10	0	0	0	256	512	640

Source: Kurz et al. (2007).

Appendix Table A2. Estimated Number of Sections of Land for Full-scale and Half-scale Waffle, by Land Type, Relief Contour, County, and State

State/County	Land Type	Relief Contour	Waffle Size Half-scale	Waffle Size Full-scale
North Dakota				
Barnes	Cropland	0 - 2	0	0
		2 - 4	2	4
		4 - 10	47	94
	Pasture	0 - 2	0	0
		2 - 4	0	1
		4 - 10	6	12
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	1	1
Benson	Cropland	0 - 2	0	0
		2 - 4	0	0
		4 - 10	5	10
	Pasture	0 - 2	0	0
		2 - 4	0	0
		4 - 10	2	3
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	1	1
Cass	Cropland	0 - 2	34	70
		2 - 4	59	134
		4 - 10	102	205
	Pasture	0 - 2	1	2
		2 - 4	1	3
		4 - 10	2	5
	Other Land	0 - 2	1	2
		2 - 4	1	1
		4 - 10	0	0
Cavalier	Cropland	0 - 2	0	1
		2 - 4	19	31
		4 - 10	77	152
	Pasture	0 - 2	0	0
		2 - 4	1	3
		4 - 10	2	3
	Other Land	0 - 2	0	0
		2 - 4	1	1
		4 - 10	2	5
Eddy	Cropland	0 - 2	0	0

Appendix Table A2. Continued

State/County	Land Type	Relief Contour	Waffle Size Half-scale	Waffle Size Full-scale
Eddy-cont.	Cropland	2 - 4	2	4
		4 - 10	0	0
	Pasture	0 - 2	0	0
		2 - 4	2	3
		4 - 10	0	0
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
Foster	Cropland	0 - 2	0	0
		2 - 4	1	2
		4 - 10	0	0
	Pasture	0 - 2	0	0
		2 - 4	0	1
		4 - 10	0	0
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
Grand Forks	Cropland	0 - 2	30	52
		2 - 4	43	87
		4 - 10	42	88
	Pasture	0 - 2	1	2
		2 - 4	3	4
		4 - 10	5	7
	Other Land	0 - 2	1	1
		2 - 4	0	1
		4 - 10	0	2
Griggs	Cropland	0 - 2	0	0
		2 - 4	5	12
		4 - 10	0	0
	Pasture	0 - 2	0	0
		2 - 4	2	4
		4 - 10	0	0
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
McHenry	Cropland	0 - 2	0	0
		2 - 4	0	0
		4 - 10	1	3
	Pasture	0 - 2	0	0
		2 - 4	0	0

Appendix Table A2. Continued

State/County	Land Type	Relief Contour	Waffle Size Half-scale	Full-scale
McHenry-cont.	Pasture	4 - 10	6	8
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	1	2
Nelson	Cropland	0 - 2	0	0
		2 - 4	1	2
		4 - 10	11	25
	Pasture	0 - 2	0	0
		2 - 4	0	1
		4 - 10	3	6
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	1	2
Pembina	Cropland	0 - 2	23	48
		2 - 4	61	120
		4 - 10	29	57
	Pasture	0 - 2	2	2
		2 - 4	2	6
		4 - 10	1	1
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
Pierce	Cropland	0 - 2	0	0
		2 - 4	0	0
		4 - 10	8	16
	Pasture	0 - 2	0	0
		2 - 4	0	0
		4 - 10	3	9
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
Ransom	Cropland	0 - 2	0	1
		2 - 4	0	0
		4 - 10	17	35
	Pasture	0 - 2	0	0
		2 - 4	0	0
		4 - 10	22	39
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0

Appendix Table A2. Continued

		Relief	Waffle Size	
State/County	Land Type	Contour	Half-scale	Full-scale
Richland	Cropland	0 - 2	40	87
		2 - 4	48	94
		4 - 10	47	102
	Pasture	0 - 2	2	5
		2 - 4	4	6
		4 - 10	6	14
	Other Land	0 - 2	0	3
		2 - 4	1	4
		4 - 10	4	5
Rolette	Cropland	0 - 2	0	0
		2 - 4	0	0
		4 - 10	1	1
	Pasture	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	1
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
Sargent	Cropland	0 - 2	0	1
		2 - 4	8	22
		4 - 10	54	106
	Pasture	0 - 2	0	0
		2 - 4	1	3
		4 - 10	8	15
	Other Land	0 - 2	0	0
		2 - 4	2	2
		4 - 10	2	3
Sheridan	Cropland	0 - 2	0	0
		2 - 4	0	0
		4 - 10	5	9
	Pasture	0 - 2	0	0
		2 - 4	0	0
		4 - 10	5	9
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	1	1
Steele	Cropland	0 - 2	0	1
		2 - 4	8	13
		4 - 10	23	44
	Pasture	0 - 2	0	0

Appendix Table A2. Continued

State/County	Land Type	Relief Contour	Waffle Size Half-scale	Waffle Size Full-scale
Steele-cont.	Pasture	2 - 4	0	1
		4 - 10	1	3
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	2	2
Towner	Cropland	0 - 2	0	0
		2 - 4	0	1
		4 - 10	8	14
	Pasture	0 - 2	0	0
		2 - 4	0	0
		4 - 10	1	2
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	1
Traill	Cropland	0 - 2	37	67
		2 - 4	54	100
		4 - 10	44	85
	Pasture	0 - 2	0	1
		2 - 4	1	1
		4 - 10	0	1
	Other Land	0 - 2	0	0
		2 - 4	2	2
		4 - 10	1	1
Walsh	Cropland	0 - 2	18	36
		2 - 4	31	57
		4 - 10	23	48
	Pasture	0 - 2	2	3
		2 - 4	3	5
		4 - 10	2	4
	Other Land	0 - 2	0	0
		2 - 4	0	1
		4 - 10	2	3
Wells	Cropland	0 - 2	0	0
		2 - 4	0	0
		4 - 10	14	26
	Pasture	0 - 2	0	0
		2 - 4	0	0
		4 - 10	5	8
	Other Land	0 - 2	0	0
		2 - 4	0	0

Appendix Table A2. Continued

State/County	Land Type	Relief Contour	Waffle Size Half-scale	Full-scale
Wells-cont.	Other Land	4 - 10	0	0
Minnesota				
Becker	Cropland	0 - 2	0	0
		2 - 4	4	5
		4 - 10	12	26
	Pasture	0 - 2	0	0
		2 - 4	0	0
		4 - 10	1	2
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	1	1
Beltrami	Cropland	0 - 2	0	1
		2 - 4	1	3
		4 - 10	0	0
	Pasture	0 - 2	0	0
		2 - 4	1	1
		4 - 10	0	0
	Other Land	0 - 2	4	9
		2 - 4	13	24
		4 - 10	0	0
Big Stone	Cropland	0 - 2	0	0
		2 - 4	1	1
		4 - 10	0	0
	Pasture	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
Clay	Cropland	0 - 2	31	62
		2 - 4	41	85
		4 - 10	11	25
	Pasture	0 - 2	1	3
		2 - 4	2	4
		4 - 10	0	1
	Other Land	0 - 2	0	0
		2 - 4	1	2
		4 - 10	0	0
Clearwater	Cropland	0 - 2	1	3
		2 - 4	3	7

Appendix Table A2. Continued

State/County	Land Type	Relief Contour	Waffle Size Half-scale	Waffle Size Full-scale
Clearwater	Cropland	4 - 10	0	0
	Pasture	0 - 2	1	1
		2 - 4	2	4
		4 - 10	0	0
	Other Land	0 - 2	11	19
		2 - 4	16	35
		4 - 10	0	2
Grant	Cropland	0 - 2	2	7
		2 - 4	26	39
		4 - 10	6	13
	Pasture	0 - 2	0	0
		2 - 4	1	1
		4 - 10	0	0
	Other Land	0 - 2	0	0
		2 - 4	1	1
		4 - 10	0	1
Kittson	Cropland	0 - 2	20	39
		2 - 4	33	80
		4 - 10	21	43
	Pasture	0 - 2	2	3
		2 - 4	3	6
		4 - 10	2	4
	Other Land	0 - 2	18	40
		2 - 4	27	50
		4 - 10	5	9
Lake of the Woods	Cropland	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
	Pasture	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
	Other Land	0 - 2	0	1
		2 - 4	1	1
		4 - 10	0	0
Mahnomen	Cropland	0 - 2	0	0
		2 - 4	5	8
		4 - 10	20	35
	Pasture	0 - 2	0	0
		2 - 4	0	1

Appendix Table A2. Continued

State/County	Land Type	Relief Contour	Waffle Size Half-scale	Waffle Size Full-scale
Mahnomen	Pasture	4 - 10	1	2
	Other Land	0 - 2	1	1
		2 - 4	2	4
		4 - 10	3	7
Marshall	Cropland	0 - 2	34	61
		2 - 4	74	151
		4 - 10	16	30
	Pasture	0 - 2	2	3
		2 - 4	3	7
		4 - 10	1	1
	Other Land	0 - 2	8	19
		2 - 4	18	36
		4 - 10	4	9
Norman	Cropland	0 - 2	25	53
		2 - 4	30	65
		4 - 10	35	73
	Pasture	0 - 2	0	1
		2 - 4	1	1
		4 - 10	1	1
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	3	3
Otter Tail	Cropland	0 - 2	0	0
		2 - 4	0	1
		4 - 10	2	4
	Pasture	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
Pennington	Cropland	0 - 2	17	33
		2 - 4	40	79
		4 - 10	2	3
	Pasture	0 - 2	1	3
		2 - 4	3	7
		4 - 10	0	0
	Other Land	0 - 2	2	5
		2 - 4	3	6
		4 - 10	0	0

Appendix Table A2. Continued

State/County	Land Type	Relief Contour	Waffle Size Half-scale	Full-scale
Polk	Cropland	0 - 2	58	104
		2 - 4	74	151
		4 - 10	32	62
	Pasture	0 - 2	2	4
		2 - 4	3	5
		4 - 10	1	2
	Other Land	0 - 2	2	3
		2 - 4	5	8
		4 - 10	3	3
Red Lake	Cropland	0 - 2	7	11
		2 - 4	17	35
		4 - 10	0	0
	Pasture	0 - 2	0	1
		2 - 4	1	2
		4 - 10	0	0
	Other Land	0 - 2	1	6
		2 - 4	2	5
		4 - 10	0	0
Roseau	Cropland	0 - 2	11	23
		2 - 4	19	43
		4 - 10	0	0
	Pasture	0 - 2	0	1
		2 - 4	1	2
		4 - 10	0	0
	Other Land	0 - 2	9	14
		2 - 4	12	23
		4 - 10	0	1
Stevens	Cropland	0 - 2	2	4
		2 - 4	5	19
		4 - 10	0	0
	Pasture	0 - 2	0	0
		2 - 4	0	1
		4 - 10	0	0
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
Traverse	Cropland	0 - 2	31	52
		2 - 4	49	96
		4 - 10	9	18
	Pasture	0 - 2	1	1

Appendix Table A2. Continued

		Relief	Waffle Size	
State/County	Land Type	Contour	Half-scale	Full-scale
Traverse	Pasture	2 - 4	2	4
		4 - 10	0	1
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	1
Wilkin	Cropland	0 - 2	28	52
		2 - 4	62	139
		4 - 10	16	34
	Pasture	0 - 2	1	1
		2 - 4	1	3
		4 - 10	0	1
	Other Land	0 - 2	1	1
		2 - 4	0	0
		4 - 10	0	0
South Dakota				
Marshall	Cropland	0 - 2	0	0
		2 - 4	0	0
		4 - 10	1	1
	Pasture	0 - 2	0	0
		2 - 4	1	1
		4 - 10	1	2
	Other Land	0 - 2	0	0
		2 - 4	0	0
		4 - 10	0	0
Roberts	Cropland	0 - 2	0	0
		2 - 4	1	2
		4 - 10	16	31
	Pasture	0 - 2	0	0
		2 - 4	1	1
		4 - 10	6	11
	Other Land	0 - 2	0	0
		2 - 4	0	1
		4 - 10	0	4

Source: Kurz et al. (2007).

APPENDIX B

Estimation of Structural and Installation Costs for Culvert Control Devices, Selected Watersheds, Red River Basin, 2005

The following text explains how the structural and installation costs for culvert control devices were estimated. Text and numerical data were provided by the Energy & Environmental Research Center.

1) The permit data from three Watershed Districts (WSD's) were evaluated and compiled into three representative size distributions. The three distributions were titled after their respective WSD's: Pembina County, Two Rivers, and the Red Lake.

The raw data were also adjusted to eliminate non-feasible modifications and to reduce the data set size. This was performed by:

   a. Eliminating the excessively large round sizes and all box culverts.
   b. Resizing pipe arches to their corresponding round sizes.

2) The expected number of modifications per relief category was determined. The estimated number of modifications per relief category are contained in Appendix Table B1.

3) The WSD distributions were applied to the cost associated with each size of expected modification to determine an average cost for each type of structure modification, whether standpipe or isolation valve.

Example: If 35 percent of the culverts were 24-inch and 65% were 36-inch and the 24-inch valve cost $800 and the 36-inch valve cost $1,200 then by multiplying 0.35 by 800 and adding the result of multiplying 1,200 by 0.65 yields an average cost of a valve to be $1,060.

The stand pipe average was then adjusted to include the costs associated with the anchoring process.

4) The average component cost was applied to the expected number of modifications per relief category which produced an average cost required to modify one section in each relief category (Appendix Table B1).

5) By adding the estimated average contractor's cost, expected cost required to modify sections of each relief category was determined.

6) The EERC Waffle research team questioned the validity of the three distributions, but believed the data were sufficient to determine a safe working value. The Red Lake WSD is the largest of the WSD's used in this analysis and encompasses both areas near and far from the Red River.

7) Possible problems with how representative the sample WSDs are compared to other districts in the Basin:

- a. The permit database may not be complete.
- b. The data base may not show a true sampling of culvert sizes.
- c. The distributions are assumed to be representative for all WSD's including those not located relatively close to the river.
- d. The distributions are all from MN WSD's and are being used to approximate ND watersheds.

Appendix Table B1. Cost Factors for Culvert Modifications, per Section of Land, Various Watersheds, Red River Basin, 2005

		Red Lake Watershed	
Relief Category	Description of Structural Modifications	Infrastructure Costs	Installation Costs
0 - 2	2 standpipes with 4 drains	$11,564.01	$1,200.00
2 - 4	2 standpipes with 2 drains	$9,393.87	$1,000.00
4 - 10	1 standpipe with 1 drain	$3,611.87	$800.00
		Pembina County Watershed	
Relief Category	Description of Structural Modifications	Infrastructure Costs	Installation Costs
0 - 2	2 standpipes with 4 drains	$14,844.13	$1,200.00
2 - 4	2 standpipes with 2 drains	$12,312.50	$1,000.00
4 - 10	1 standpipe with 1 drain	$4,890.44	$800.00
		Two Rivers Watershed	
Relief Category	Description of Structural Modifications	Infrastructure Costs	Installation Costs
0 - 2	2 standpipes with 4 drains	$14,844.13	$1,200.00
2 - 4	2 standpipes with 2 drains	$12,312.50	$1,000.00
4 - 10	1 standpipe with 1 drain	$4,890.44	$800.00

Source: Kurz et al. (2007).

APPENDIX C

Cash Rent Data, Population Projections, Aggregate Residential and Commercial Property Values, Consumer Price Index for Housing, and Office of Federal Housing Enterprise Oversight Housing Value Index

Appendix Table C1. Cash Rents, by Land Type, County, and State, 2004 and 2005

State/County	Non-irrigated Cash Rents Cropland	Pasture
North Dakota (2005 data)	- $/acre-	- $/acre-
Barnes	39.7	13.2
Benson	31.1	11.1
Cass	59.2	25
Cavalier	40.6	11.4
Eddy	32.3	11
Foster	36.5	12.3
Grand Forks	49.5	12.3
Griggs	35.8	11.4
McHenry	33.5	12.6
Nelson	32.8	10.9
Pembina	58.5	11
Pierce	31.4	12.6
Ransom	47.1	18.6
Richland	68.2	22.1
Rolette	32	13.7
Sargent	50.5	22.6
Sheridan	28.5	10.9
Steele	43.9	11
Towner	31.8	11.2
Traill	59.8	14.2
Walsh	52.8	$9.50
Wells	33.8	11.8
South Dakota (2005 data)		
Marshall	56.2	22.7
Roberts	67.7	24.3
Minnesota (2004 data)		
Becker	44	14.56
Beltrami	18.82	6.23
Big Stone	64	21.18
Clay	70	23.17
Clearwater	48.02	15.89
Grant	78	25.81
Kittson	32.6	10.79
Lake of the Woods	26.26	8.69
Mahnomen	52	17.21
Marshall	36	11.91
Norman	61	20.19
Otter Tail	42	13.9
Pennington	39.21	12.98
Polk	50	16.55
Red Lake	31.09	10.29
Roseau	28.15	9.32
Stevens	75	24.82
Traverse	71.61	23.7

Sources: National Agricultural Statistics Service (2005a, 2005b) and Hachfeld et al. (2005).

Appendix Table C2. Population Projections, Study Cities, 2005 through 2050

City	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Main Population Projection										
Drayton	920	920	920	920	920	920	920	920	920	920
Fargo	98800	107,100	116,700	126,400	136,900	147400	159,200	171,000	187,700	204,300
Grafton	4,450	4,420	4,410	4,420	4,410	4380	4,330	4,250	4,180	4,130
Grand Forks	52,000	54,800	57,800	61,000	64,300	67800	71,500	75,300	79,400	83,800
Wahpeton	8,940	9,300	9,650	10,010	10360	10720	11,070	11,430	11,780	12,140
Breckenridge	3460	3,360	3,250	3,150	3,050	2,950	2,850	2,740	2,640	2540
East Grand Forks	7700	7,900	8,100	8,300	8,600	8,800	9,000	9,300	9,500	9,800
Moorhead	34,700	35,800	36,800	37,900	38,900	40,000	41,000	42,100	43,100	44,200
Crookston	7826	7,775	7,724	7,674	7,623	7,573	7,522	7,472	7,421	7370
Pessimistic or Low Population Projection										
Drayton	920	889	858	827	796	766	735	704	673	642
Fargo	98,800	109,016	119,232	129,448	139,664	149,879	160,095	170,311	180,527	190,743
Grafton	4,450	4,258	4,066	3,874	3,682	3,490	3,298	3,106	2,914	2,722
Grand Forks	52,000	53,275	54,549	55,824	57,098	58,373	59,647	60,922	62,196	63,471
Wahpeton	8,940	8,824	8,707	8,591	8,474	8,358	8,241	8,125	8,008	7,892
Breckenridge	3,460	3,360	3,250	3,150	3,050	2,950	2,850	2,740	2,640	2,540
East Grand Forks	7,700	7,933	8,167	8,400	8,633	8,867	9,100	9,333	9,567	9,800
Moorhead	34,700	34,499	34,299	34,098	33,898	33,697	33,497	33,296	33,096	32,895
Crookston	8114	8,061	8,008	7,955	7,901	7,848	7,795	7,742	7,689	7636
Optimistic or High Population Projection										
Drayton	920	920	920	920	920	920	920	920	920	920
Fargo	98,800	114,830	130,861	146,891	162,921	178952	194,982	211,012	227,043	243,073
Grafton	4,450	4,649	4,849	5,048	5,247	5,447	5,646	5,845	6,045	6,244
Grand Forks	52,000	56,181	60,362	64,544	68,725	72,906	77,087	81,269	85,450	89,631
Wahpeton	8,940	9,296	9,651	10,007	10,362	10,718	11,073	11,429	11,784	12140
Breckenridge	3,460	3,476	3,491	3,507	3,523	3,538	3,554	3,570	3,585	3,601
East Grand Forks	7,700	8,358	9,015	9,673	10,331	10,988	11,646	12,304	12,961	13,619
Moorhead	34,700	37,168	39,635	42103	44,571	47,038	49,506	51,973	54,441	56,909
Crookston	8,114	8,446	8,778	9110	9,442	9,774	10,107	10,439	10,771	11103

Sources: Minnesota State Demographic Center (2002), Bureau of Reclamation (2005), Northwest Economic Associates (2003).

Appendix Table C3. Aggregate Residential Property Values, Net of Land, Nominal and Real, 1990 through 2004

	Fargo	Moorhead	Grand Forks	East Grand Forks	Wahpeton	Breckenridge	Drayton	Grafton	Crookston
------ Nominal Values (000s $) ------									
1990	811,688	443,318	608,061	106131	74,621	42,381	not available	50,723	not available
1991	841,106	459,386	632,306	110,363	77,597	44,071	not available	50,910	not available
1992	862,656	471,155	639,590	111,634	78,357	44,503	not available	50,941	not available
1993	919,459	502,179	673,047	117,474	79,228	44,998	not available	50,858	86,614
1994	1,007,349	519,937	733,379	126,855	85,634	50,479	not available	51,176	92,132
1995	1,083,054	558,934	803257	137,684	87,010	53,163	11,405	51,800	97,650
1996	1,161,038	582,133	850,741	144,490	95,071	60,134	11,417	52,331	103,168
1997	1,247,400	617,516	817,156	137,506	96,304	62,987	11,543	52,967	108,686
1998	1,328,450	626,711	877,076	146,215	94,225	63,655	12,052	53,919	114,205
1999	1,467,360	575,125	952,771	157,341	96,121	67,005	12,747	55,349	119,723
2000	1,573,578	709,622	994,097	165,884	96,851	68,488	10,736	56,131	121,829
2001	1,666,267	764,420	1,006,598	169,711	97,656	70,039	10,873	60,884	123,936
2002	1,831,160	823,733	1,051,685	179,131	105,632	76,822	11,112	62,005	126,043
2003	1,971,970	896,290	1,117,827	192,329	105,789	78,000	10,962	62,655	128,150
2004	2,124,103	1,030,776	1,220,057	212028	112,018	83,719	10,958	63,470	130,256
------ Real Values (000s 2004 $) ------									
1990	1,034,094	564,789	766,603	133,803	95,616	70,389	not available	64,994	not available
1991	1,079,772	589,737	806,915	140,839	99,695	72,947	not available	65,408	not available
1992	1,089,174	594,872	798,162	139,312	99,184	73,698	not available	64,482	not available
1993	1,149,568	627,857	804,109	140,350	97,423	73,397	not available	62,538	141,280
1994	1,256,030	648,292	816,315	141,201	102,438	81,554	not available	61,218	148,848
1995	1,330,236	686,498	906,113	155,314	102,154	83,036	13,390	60,815	152,521
1996	1,431,845	717,913	969,447	164,652	111,090	92,798	13,341	61,149	159,207
1997	1,508,295	746,670	902,947	151,943	111,325	94,360	13,343	61,229	162,823
1998	1,562,758	737,248	974,432	162,445	106,783	92,216	13,659	61,105	165,445
1999	1,731,936	678,825	1,092,427	180,404	110,766	90,784	14,689	63,781	162,211
2000	1,862,594	839,957	1,150,125	191,921	111,700	86,842	12,382	64,736	154,479
2001	1,934,396	887427	1,146,685	193,329	111,510	83,865	12,416	69,522	148,401
2002	2,041,952	918556	1,167,097	198,788	116,554	86,437	12,261	68,416	141,818
2003	2,077,381	944201	1,203,938	207,145	112,798	82,633	11,688	66,806	135,762
2004	2,124,103	1030776	1220057	212,028	112,018	83,719	10,958	63470	130256

Sources: Nominal values obtained from various city and county agencies.

Appendix Table C4. Aggregate Commercial Property Values, Net of Land, Nominal and Real, 1990 through 2004

	Fargo	Moorhead	Grand Forks	East Grand Forks	Wahpeton	Breckenridge	Drayton	Grafton	Crookston
Nominal Values (000s $)									
1990	733940	95,558	446,503	31,766	53,658	6,682	not available	28,411	not available
1991	759,699	98,912	451,900	32,150	52,183	6,498	not available	28,359	not available
1992	826,785	107,646	470,723	33,489	52,454	6,532	not available	27,697	not available
1993	853,311	111,100	491,902	34,995	53,496	6,662	not available	27,626	19,297
1994	884,654	116,905	500,509	34,754	53,653	7,072	not available	26,752	21,022
1995	971,222	123,762	525,921	35,621	55,666	7,743	3,728	26,985	22,747
1996	1,015,578	126,515	543,304	35,872	59,058	8,645	3,724	27,579	24,472
1997	1,065,395	128,728	554,315	35,653	63,030	9,686	3,779	26,238	26,197
1998	1,132,425	131,127	591,619	37,043	62,136	10,001	3,875	26,672	27,922
1999	1,199,264	136,574	626,100	38,134	65,445	11,011	3,703	28,981	29,647
2000	1,312,767	145,186	689,383	41,673	68,266	11,535	4,019	29,094	31,237
2001	1,454,791	153,679	723,171	43,383	69,728	11,832	3,987	29,301	32,827
2002	1,509,339	172,244	742,887	44,226	70,369	11,992	3,943	29,927	34,417
2003	1,595,699	190,274	786,323	46,451	77,079	13,191	3,915	32,015	36,007
2004	1,678,186	201,590	841,330	49,315	79,050	13,586	3,808	31364	37597
Real Values (000s 2004 $)									
1990	532126	69,282	323,727	26,521	38904	4,845	not available	20,599	not available
1991	634,269	82,581	377,289	26,842	43,567	5,425	not available	23,677	not available
1992	793,911	103,366	452,007	32,157	50,369	6,272	not available	26,596	not available
1993	915,894	119,248	527,978	37,562	57,420	7,150	not available	29,652	20,713
1994	979,126	129,389	553,958	38,465	59,382	7,827	not available	29,608	23,267
1995	1,064,955	135,706	576,678	39,059	61,039	8,490	4,088	29,589	24,943
1996	1,089,162	135,682	582,669	38,471	63,337	9,272	3,994	29,577	26,245
1997	1,091,799	131,918	568,053	36,537	64,593	9,926	3,873	26,888	26,846
1998	1,102,984	127,718	576,239	36,080	60,520	9,741	3,774	25,978	27,196
1999	1,155,137	131,549	603,063	36,731	63,037	10,605	3,567	27,915	28,556
2000	1,232,848	136,348	647415	39,136	64,110	10,832	3,775	27,323	29,335
2001	1,394,851	147,348	693,375	41,596	66,855	11,345	3,823	28,094	31,474
2002	1,504,831	171,729	740,668	44,094	70,159	11,956	3,932	29,838	34314
2003	1,623,657	193,608	800,100	47,265	78,429	13,422	3,984	32,576	36,638
2004	1,678,186	201,590	841,330	49315	79,050	13,586	3,808	31,364	37597

Sources: Nominal values obtained from various city and county agencies.

Appendix Table C5. Office of Federal Housing Enterprise Oversight Housing Price Index, Nominal and Real, 1990 through 2004

	Fargo/Moorhead		Grand Forks/E.G.Forks		North Dakota		Minnesota	
	Nominal	Real	Nominal	Real	Nominal	Real	Nominal	Real
1990	85.55	126.16	79.98	117.95	114.33	168.60	139	204.98
1991	88.27	125.20	82.15	116.52	118.55	168.15	145.01	205.68
1992	92.37	127.30	86.46	119.16	123.84	170.67	149.17	205.58
1993	95.79	128.56	92.74	124.46	130.91	175.69	155.52	208.72
1994	98.50	128.91	102.08	133.59	138.00	180.60	161.02	210.73
1995	102.55	130.86	103.30	131.82	144.20	184.01	170.81	217.97
1996	105.09	130.33	105.22	130.49	149.08	184.89	177.89	220.62
1997	109.99	132.93	111.35	134.57	154.64	186.89	188.04	227.25
1998	115.65	136.63	113.29	133.84	161.36	190.63	198.92	235.01
1999	117.78	136.18	112.17	129.69	162.15	187.48	217.33	251.28
2000	121.53	135.79	115.03	128.53	167.65	187.32	240.30	268.50
2001	128.88	138.45	121.51	130.53	176.12	189.20	264.67	284.33
2002	137.14	144.14	127.49	134.00	186.29	195.80	287.89	302.58
2003	148.79	152.57	134.64	138.06	197.59	202.62	313.39	321.36
2004	160.73	160.73	148.7	148.7	216.04	216.04	340.45	340.45

Notes: Real values expressed in 2004 dollars. Nominal values converted to real values using Consumer Price Index for Housing. Values for each year are fourth quarter figures.
Source: Office of Federal Housing Enterprise Oversight (2006).

Appendix Table C6. Consumer Price Index for Housing, United States, 1990 through 2004

Year	Index
1990	128.5
1991	133.6
1992	137.5
1993	141.2
1994	144.8
1995	148.5
1996	152.8
1997	156.8
1998	160.4
1999	163.9
2000	169.6
2001	176.4
2002	180.3
2003	184.8
2004	189.5

Source: U.S. Department of Labor (2006).

Appendix Table C7. Gross Domestic Product-Implicit Price Deflator, United States, 1990 through 2004

Year	Index
1990	81.59
1991	84.444
1992	86.385
1993	88.381
1994	90.259
1995	92.106
1996	93.852
1997	95.414
1998	96.472
1999	97.868
2000	100.000
2001	102.399
2002	104.187
2003	106.305
2004	109.099

Source: U.S. Department of Commerce (2006).

Appendix Table C8. Index of Cash Rent Paid for Farmland, United States, 1990 through 2004

Year	Nominal	Real
1990	92.0	123.0
1991	108.0	139.5
1992	100.0	126.3
1993	110.0	135.8
1994	115.0	139.0
1995	126.0	149.2
1996	129.0	150.0
1997	135.0	154.4
1998	135.0	152.7
1999	137.0	152.7
2000	139.0	151.6
2001	143.0	152.4
2002	143.0	149.7
2003	145.0	148.8
2004	145.0	145.0

Notes: Nominal cash rent index adjusted for inflation using Gross Domestic Product-Implicit Price Deflator.
Source: U.S. Department of Agriculture (1997, 2005).

APPENDIX D

Original and Projected Flood-stage Damage Functions, Flood Frequencies, and Crest Elevations, Various Years

Appendix Table D1. Flood-stage Damage Function, Fargo/Moorhead/Oakport Township, 2004

	Flood-related Damages			
Elevation[a]	Public	Residential	Commercial[b]	Total
– msl --	-- 000s 2004 $			--
894				
895	516.8	863.1	3,047.4	4,427.3
896	1,641.9	1,948.8	3,983.3	7,574.0
897	3,650.0	5,312.7	4,745.1	13,707.8
898	5,450.9	25,162.1	8,610.1	39,223.1
899	7,556.9	82,890.7	16,576.6	107,024.2
900	9,382.5	230,416.6	35,397.1	275,196.2
901[c]	11,297.4	445,676.4	76,595.9	533,569.7
902	23,572.3	822,461.3	303,080.8	1,149,114.4
903	41,475.4	1,183,082.6	501,615.6	1,726,173.6
904	61,972.3	1,551,302.7	729,867.4	2,343,142.4
905	83,971.6	1,899,011.3	967,155.6	2,950,138.5
906	114,779.0	2,258,988.0	1,205,649.0	3,579,416.0

[a] Reference height (mean sea level) of the Red River at Main Avenue, Fargo, ND.

[b] Includes damages to apartment buildings.

[c] Reference height for a 100-year flood.

Source: U.S. Army Corps of Engineers (2005).

Appendix Table D2. Flood-stage Damage Function, Grand Forks and East Grand Forks, 1997

	Flood-related Damages		
Elevation[a]	Residental	Commercial[b]	Total
– msl --	------------------------- 000s 1997 $		----------------------------
823.54			
824.54	1,145.8	35.3	1,181.1
825.54	2,503.6	77.3	2,580.9
826.54	68,901.5	26,065.9	94,967.4
827.54	104,887.5	40,131.9	145,019.4
828.54	133,229.5	50,227.9	183,457.4
829.54	242,652.9	82,437.3	325,090.2
830.54	297,081.9	120,667.8	417,749.7
831.54	359,408.8	188,031.7	547,440.5
832.54	465,028.7	263,043.6	728,072.3
833.54[c]	603,999.9	325,752.0	929,751.9
834.54	709,359.5	385,995.3	1,095,354.8
835.54	769,288.0	436,206.6	1,205,494.6
836.54	817,576.2	481,307.4	1,298,883.6
837.54	860,740.4	517,015.4	1,377,755.8
838.54	902,503.2	551,859.2	1,454,362.4

[a] Reference height (mean sea level) of the Red River in Grand Forks, ND.

[b] Includes public infrastructure and apartment building damages.

[c] Maximum height for the 1997 flood in Grand Forks, ND.

Source: U.S. Army Corps of Engineers (1998).

Appendix Table D3. Flood-stage Damage Function, Wahpeton, 1999

Reference Height[a]	Flood-related Damages		
	Residental	Commercial[b]	Total
– feet --	------------------------- 000s 1999 $	-----------------------------	
-7	0.0	0.0	0.0
-6	20.8	0.0	20.8
-5	47.7	0.0	47.7
-4	9,324.1	49.5	9,373.6
-3	12,889.2	117.2	13,006.4
-2	17,366.3	272.9	17,639.2
-1	22,592.6	771.8	23,364.4
0[c]	33,815.2	2,366.4	36,181.6
1	41,668.5	6,841.0	48,509.5
2	50,229.4	13,811.7	64,041.1
3	64,379.3	23,362.2	87,741.5
4	76,938.0	36,003.3	112,941.3
5	86,164.1	48,764.5	134,928.6
6	95,614.9	62,630.8	158,245.7
7	114,363.3	75,810.5	190,173.9

[a] Reference heights are indicated as 1-foot intervals above or below the crest elevation of the Red River in a 100-year flood. Separate flood-stage damage functions were prepared for various areas within the city of Wahpeton with each area having a slightly different crest height for a 100-year flood. The various areas were combined using reference heights above and below a 100-year flood.

[b] Includes public infrastructure and apartment building damages.

[c] Zero elevation refers to the height of the Red River in a 100-year flood.

Source: U.S. Army Corps of Engineers (2000b).

Appendix Table D4. Flood-stage Damage Function, Breckenridge, 1999

Reference Height[a]	Flood-related Damages		
	Residental	Commercial[b]	Total
– feet --	------------------------- 000s 1999 $	----------------------------	
-7	0.0	0.0	0.0
-6	0.0	0.0	0.0
-5	1,334.9	0.5	1,335.4
-4	1,894.1	83.7	1,977.8
-3	4,361.5	350.2	4,711.7
-2	10,178.3	4,434.7	14,613.0
-1	17,452.8	6,406.7	23,859.5
0[c]	26,334.9	10,586.7	36,921.6
1	32,165.6	16,750.5	48,916.1
2	40,457.9	21,524.3	61,982.2
3	51,215.6	25,843.2	77,058.8
4	59,436.5	29,280.2	88,716.7
5	65,029.1	30,194.0	95,223.1
6	68,821.7	34,868.7	103,690.4
7	72,484.0	37,048.2	109,532.2

[a] Reference heights are indicated as 1-foot intervals above or below the crest elevation of the Red River in a 100-year flood. Separate flood-stage damage functions were prepared for various areas within the city of Breckenridge with each area having a slightly different crest height for a 100-year flood. The various areas were combined using reference heights above and below a 100-year flood.

[b] Includes public infrastructure and apartment building damages.

[c] Zero elevation refers to the height of the Red River in a 100-year flood.

Source: U.S. Army Corps of Engineers (2000a).

Appendix Table D5. Flood-stage Damage Function, Grafton, 2002

	Flood-related Damages			
Elevation[a]	Public	Residential	Commercial[b]	Total
– msl --	-- 000s 2002 $			--
820	0.0	0.0	0.0	0.0
821	12.5	0.0	0.0	12.5
822	34.0	0.0	0.0	34.0
823	55.4	455.4	1.6	512.4
824	101.2	1,358.1	3.1	1,462.4
825	522.8	3,109.4	5.8	3,638.0
826	1,458.7	6,203.9	24.1	7,686.7
827	2,457.3	12,474.0	67.9	14,999.2
828	4,163.0	21,688.6	173.0	26,024.6
829	5,560.5	31,027.8	449.2	37,037.5
830[c]	7,047.1	40,691.8	1,426.0	49,164.9
831	9,327.0	55,044.1	3,943.0	68,314.1

[a] Reference height (mean sea level) of the Park River in Grafton, ND.

[b] Includes damages to apartment buildings.

[c] Reference height for a 100-year flood.

Source: U.S. Army Corps of Engineers (2003).

Appendix Table D6. Flood-stage Damage Function, Drayton, 2003

	Flood-related Damages			
Elevation[a]	Public	Residential	Commercial[b]	Total
– msl --	-- 000s 2003 $			--
792.8	34.5	47.2	2.8	84.4
795.24	91.3	125.0	7.3	223.6
796.97	228.0	312.3	18.2	558.4
798.83	1,120.6	1,535.5	89.3	2,745.4
800.06[c]	2,773.0	3,799.5	221.0	6,793.5
802.87	5,763.3	7,896.7	459.4	14,119.3

[a] Reference height (mean sea level) of the Red River in Drayton, ND.

[b] Includes damages to apartment buildings.

[c] Reference height for a 100-year flood.

Source: U.S. Army Corps of Engineers (2004).

Appendix Table D7. Flood-stage Damage Function, Crookston, 1997

Reference Height[a]	Flood-related Damages		
	Residental	Commercial[b]	Total
– feet --	------------------------- 000s 1995 $		-----------------------------
-13	0.0	0.0	0.0
-12	247.0	0.0	247.5
-11	804.6	0.0	804.6
-10	1,100.6	0.0	1,100.6
-9	1,707.6	0.0	1,707.6
-8	2,532.7	3.4	2,536.1
-7	3,177.1	9.1	3,186.2
-6	4,339.1	14.9	4,353.9
-5	5,611.7	18.5	5,630.2
-4	7,690.2	69.5	7,729.8
-3	9,188.9	106.7	9,295.6
-2	10,693.9	198.5	10,892.4
-1	12,293.1	323.8	12,616.9
0[c]	14,071.5	652.0	14,723.6
1	16,789.7	1,128.8	17,918.5
2	18,765.4	1,674.4	20,439.8
3	20,657.9	2,357.9	23,015.9
4	22,152.6	3,062.3	25,215.0
5	23,381.8	3,890.1	27,271.9

[a] Reference heights are indicated as 1-foot intervals above or below the crest elevation of the Red Lake River in a 100-year flood. Separate flood-stage damage functions were prepared for various areas within the city of Crookston with each area having a slightly different crest height for a 100-year flood. The various areas were combined using reference heights above and below a 100-year flood.

[b] Includes public infrastructure and apartment building damages.

[c] Zero refers to the crest height of the Red Lake River in a 100-year flood.

Source: U.S. Army Corps of Engineers (1997).

Appendix Table D8. Flood Frequency and Crest Heights for Flood-stage Damage Function, Grand Forks and East Grand Forks, 2005

U.S. Army Corps of Engineers Data			Flood-Stage Damage Function[a]		
Recurrence Interval	Flood Frequency	Crest Height (msl)	Crest Height (msl)	Flood Damages (000s $)	Interpolated/ Extrapolated Flood Frequency
			823.54	0	0.10659
10-year	0.1	823.78	824.54	1335	0.08628
			825.54	2916	0.06823
20-year	0.05	826.55	826.54	117412	0.05018
			827.54	179436	0.04113
			828.54	226761	0.03218
50-year	0.02	829.9	829.54	398969	0.02322
			830.54	519095	0.01697
			831.54	693255	0.01223
100-year	0.01	832.01	832.54	927641	0.00897
			833.54	1244748	0.00702
200-year	0.005	834.58	834.54	1504872	0.00508
			835.54	1677575	0.00404
			836.54	1823938	0.00303
500-year	0.002	837.57	837.54	1947620	0.00203
			838.54	2067745	0.00103

[a] Function has not been adjusted for structural protections added since 1997.

Source: U.S. Army Corps of Engineers (1998).

Appendix Table D9. Flood Frequency and Crest Heights for Flood-stage Damage Function, Wahpeton, 2005

U.S. Army Corps of Engineers Data			Flood-Stage Damage Function[a]		
Recurrence Interval	Flood Frequency	Crest Height (ft)[b]	Crest Height (ft)[b]	Flood Damages (000s $)	Interpolated/ Extrapolated Flood Frequency
			-7	0	0.25147
5-year	0.2	-6.437	-6	24	0.17043
10-year	0.1	-4.96	-5	56	0.10271
			-4	10947	0.0653
20-year	0.05	-3.577	-3	15194	0.04104
			-2	20615	0.02549
50-year	0.02	-1.647	-1	27340	0.01607
100-year	0.01	0	0	57333	0.01
			1	82516	0.00769
200-year	0.005	2.163	2	112580	0.00538
			3	159811	0.00403
500-year	0.002	4.757	4	206930	0.00288
			5	245883	0.00159
			6	286777	0.00125
			7	350013	0.00086

[a] Function has not been adjusted for structural protections added since 1997.

[b] Crest heights shown are 1 foot increments above and below 100-year reference elevation.

Source: U.S. Army Corps of Engineers (2000b).

Appendix Table D10. Flood Frequency and Crest Heights for Flood-stage Damage Function, Breckenridge, 2005

U.S. Army Corps of Engineers Data			Flood-Stage Damage Function[a]		
Recurrence Interval	Flood Frequency	Crest Height (ft)[b]	Crest Height (ft)[b]	Flood Damages (000s $)	Interpolated/ Extrapolated Flood Frequency
			-7	0	0.25865
5-year	0.2	-6.435	-6	0	0.16965
10-year	0.1	-5.002	-5	1719	0.09994
			-4	2545	0.06431
20-year	0.05	-3.598	-3	6061	0.04066
			-2	18746	0.02505
50-year	0.02	-1.677	-1	30620	0.01596
100-year	0.01	0	0	47961	0.01
			1	63694	0.0077
200-year	0.005	2.178	2	80991	0.00541
			3	101046	0.00392
500-year	0.002	4.452	4	116547	0.0026
			5	125280	0.00128
			6	136359	0.001
			7	144089	0.0008

[a] Function has not been adjusted for structural protections added since 1997.
[b] Crest heights shown are 1 foot increments above and below 100-year reference elevation.
Source: U.S. Army Corps of Engineers (2000a).

Appendix Table D11. Flood Frequency and Crest Heights for Flood-stage Damage Function, Drayton, 2005

U.S. Army Corps of Engineers Data			Flood-Stage Damage Function		
Recurrence Interval	Flood Frequency	Crest Height (msl)	Crest Height (msl)	Flood Damages (000s $)	Interpolated/ Extrapolated Flood Frequency
			790.36	0	0.30000
5-year	0.2	792.8	792.80	85	0.20000
10-year	0.1	795.24	795.24	224	0.10000
20-year	0.05	796.97	796.97	559	0.05000
50-year	0.02	798.83	798.83	2746	0.02000
100-year	0.01	800.06	800.06	7144	0.01000
500-year	0.002	802.87	802.87	15103	0.002

Source: U.S. Army Corps of Engineers (2004).

Appendix Table D12. Flood Frequency and Crest Heights for Flood-stage Damage Function, Crookston, 2005

U.S. Army Corps of Engineers Data			Flood-Stage Damage Function[a]		
Recurrence Interval	Flood Frequency	Crest Height (ft)[a]	Crest Height (ft)[a]	Flood Damages (000s $)	Interpolated/ Extrapolated Flood Frequency
2-year	0.5	-13.183	-13	0	0.48969
			-12	340	0.43344
			-11	525	0.37719
			-10	667	0.32094
			-9	1,146	0.26469
			-8	1,924	0.20844
5-year	0.2	-7.85	-7	2,454	0.16277
			-6	3169	0.11898
10-year	0.1	-5.567	-5	4126	0.08903
			-4	5006	0.06968
			-3	6078	0.05032
50-year	0.02	-1.433	-2	7151	0.03097
			-1	8301	0.01698
100-year	0.01	0	0	9853	0.01000
			1	26669	0.00718
			2	30,601	0.00435
500-year	0.002	2.833	3	34,637	0.00153
			4	38,098	0.001
			5	41360	0.0005

[a] Crest heights shown are 1 foot increments above and below 100-year reference elevation.

Source: U.S. Army Corps of Engineers (1997).

Appendix Table D13. Flood-stage Damage Function, Flood Frequency and Crest Heights for Grafton, 2005

U.S. Army Corps of Engineers Data			Flood-Stage Damage Function		
Recurrence Interval	Flood Frequency	Crest Height (msl)	Crest Height (msl)	Flood Damages (000s $)	Interpolated/ Extrapolated Flood Frequency
2-year	0.5	817.57	820	0	0.36888
			821	13	0.31493
			822	36	0.26097
5-year	0.2	823.13	823	533	0.20701
			824	1519	0.16848
10-year	0.1	825.89	825	3784	0.13225
			826	8003	0.09643
20-year	0.05	827.43	827	15608	0.06396
50-year	0.02	829.02	828	27080	0.03925
100-year	0.01	829.93	829	38536	0.02038
200-year	0.005	830.41	830	51486	0.00927
500-year	0.002	830.45	831	71924	0.0002

Source: U.S. Army Corps of Engineers (2003).

Appendix Table D14. Projected Residential Damages for Flood-stage Damage Function, Fargo/Moorhead/Oakport Township, Baseline Population, Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	--		000s 2004 $		--	
894	0	0	0	0	0	0
895	886	992	1,108	1,225	1,342	1,459
896	2002	2,239	2,502	2,766	3,030	3,293
897	5456	6,103	6,822	7,541	8,259	8,978
898	25843	28,906	32,310	35,714	39,117	42,521
899	85133	95,225	106,438	117,651	128,863	140,076
900	236650	264,703	295,872	327,041	358,210	389,379
901	476161	593,391	739,222	897,799	1,081,493	1,288,494
902	895393	1,168,718	1,515,251	1,896,840	2,347,509	2,862,280
903	1296640	1,719,364	2,257,990	2,853,022	3,559,213	4368553
904	1706343	2,281,613	3,016,379	3,829,353	4,796,450	5,906,565
905	2093223	2,812,542	3,732,522	4,751,297	5,964,768	7,358,902
906	2493753	3,362,204	4,473,932	5,705,771	7,174,307	8862482

Source: Adapted from U.S. Army Corps of Engineers (2005).

Appendix Table D15. Projected Residential Damages for Flood-stage Damage Function, Fargo/Moorhead/Oakport Township, Optimistic Population, Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	--		000s 2004 $		--	
894	0	0	0	0	0	0
895	886	992	1,108	1,225	1,342	1,459
896	2002	2,239	2,502	2,766	3,030	3,293
897	5,456	6,103	6,822	7,541	8,259	8,978
898	25,843	28,906	32,310	35,714	39,117	42,521
899	85,133	95,225	106,438	117,651	128,863	140,076
900	236,650	264,703	295,872	327,041	358,210	389,379
901	476161	627,412	811,471	1,008,792	1,216,759	1,433,483
902	895393	1,262,288	1,713,961	2,202,110	2,719,541	3,261,054
903	1,296,640	1,869,929	2,577,735	3,344,236	4,157,855	5,010,224
904	1,706,343	2,490,374	3,459,710	4,510,428	5,626,476	6,796,251
905	2,093,223	3,076,257	4,292,556	5,611,658	7,013,288	8,482,789
906	2,493,753	3,682,812	5,154,786	6,751,742	8,449,031	10228833

Source: Adapted from U.S. Army Corps of Engineers (2005).

Appendix Table D16. Projected Residential Damages for Flood-stage Damage Function, Fargo/Moorhead/Oakport Township, Pessimistic Population, Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	--- 000s 2004 $ ---					
894	0	0	0	0	0	0
895	886	992	1,108	1,225	1,342	1,459
896	2002	2,239	2,502	2,766	3,030	3,293
897	5456	6,103	6,822	7,541	8,259	8,978
898	25843	28,906	32,310	35,714	39,117	42,521
899	85133	95,225	106,438	117,651	128,863	140,076
900	236650	264,703	295,872	327,041	358,210	389,379
901	473151	592,000	730,776	875,336	1,024,748	1,178,336
902	887116	1,164,892	1,492,021	1,835,055	2,191,437	2,559,304
903	1283323	1,713,208	2,220,610	2,753,605	3,308,077	3,881,031
904	1687878	2273078	2,964,551	3,691,509	4,448,246	5,230,608
905	2069897	2,801,760	3,667,051	4,577,168	5,524,902	6,505,007
906	2465396	3349096	4,394,337	5,494,075	6,639,546	7,824,371

Source: Adapted from U.S. Army Corps of Engineers (2005).

Appendix Table D17. Projected Residential Damages for Flood-stage Damage Function, Grafton, Baseline Population, Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	--- 000s 2004 $ ---					
822	0	0	0	0	0	0
823	478	533	594	656	717	778
824	1,427	1591	1773	1,955	2,137	2,320
825	3,266	3,642	4059	4,476	4,894	5,311
826	6,517	7,266	8099	8,931	9,764	10,596
827	13,104	14,610	16284	17958	19,632	21,305
828	22,783	25,402	28,313	31223	34,133	37,044
829	32,594	36,341	40,504	44668	48831	52995
830	43,012	47497	52,611	57,532	62252	67129
831	58483	64065	70592	76636	82183	88119

Source: Adapted from U.S. Army Corps of Engineers (2003).

Appendix Table D18. Projected Residential Damages for Flood-stage Damage Function, Grafton, Optimistic Population, Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	-----------------------	-----------------------	----------------------- 000s 2004 $	-----------------------	-----------------------	-----------------------
822	0	0	0	0	0	0
823	478	533	594	656	717	778
824	1,427	1591	1773	1,955	2,137	2,320
825	3,266	3,642	4059	4,476	4,894	5,311
826	6,517	7,266	8099	8931	9,764	10,596
827	13,104	14,610	16,284	17958	19,632	21,305
828	22,783	25,402	28,313	31223	34133	37,044
829	32,594	36,341	40,504	44,668	48831	52995
830	43,119	48,547	54,663	60,864	67144	73499
831	58751	66674	75691	84918	94342	103951

Source: Adapted from U.S. Army Corps of Engineers (2003).

Appendix Table D19. Projected Residential Damages for Flood-stage Damage Function, Grafton, Pessimistic Population, Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	-----------------------	-----------------------	----------------------- 000s 2004 $	-----------------------	-----------------------	-----------------------
822	0	0	0	0	0	0
823	478	533	594	656	717	778
824	1,427	1591	1,773	1,955	2,137	2,320
825	3,266	3642	4059	4,476	4,894	5,311
826	6,517	7,266	8099	8,931	9,764	10,596
827	13,104	14,610	16284	17958	19,632	21,305
828	22,783	25,402	28,313	31223	34,133	37,044
829	32,594	36,341	40,504	44668	48831	52,995
830	42,936	46,669	50,796	54,870	58862	62743
831	58294	62008	66081	70021	73757	77220

Source: Adapted from U.S. Army Corps of Engineers (2003).

Appendix Table D20. Projected Residential Damages for Flood-stage Damage Function, Grand Forks/East Grand Forks, by Population Scenario for Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	-------------------	-------------------	------- 000s 2004 $ -------	-------------------	-------------------	-------------------
Baseline Scenario						
836.54	0	0	0	0	0	0
837.54	1,174,449	1,446,267	1,772,607	2,122,155	2,500,316	2913057
838.54	1,242,993	1,538,213	1,893,122	2,273,689	2,685,888	3136317
Optimistic Scenario						
836.54	0	0	0	0	0	0
837.54	1178484	1,491,761	1,865,526	2,261,390	2,675,611	3,105,373
838.54	1247454	1,588,509	1,995,848	2,427,619	2,879,684	3,348,930
Pessimistic Scenario						
836.54	0	0	0	0	0	0
837.54	1,171,307	1,406,737	1,669,645	1,933,582	2,198,491	2,464,431
838.54	1,239,519	1,494,512	1,779,294	2,065,214	2,352,209	2,640,344

Source: Adapted from U.S. Army Corps of Engineers (1998).

Appendix Table D21. Projected Residential Damages for Flood-stage Damage Function, Wahpeton, by Population Scenario for Selected Years, 2006 through 2055

Elevation[a]	2006	2015	2025	2035	2045	2055
	------------	------------	000s 2004 $	------------	------------	
Baseline Scenario						
1	0	0	0	0	0	0
2	96,960	111,777	128,816	146,414	164,534	183,256
3	132,925	153,755	177,771	202,630	228,281	254,841
4	164,844	191,012	221,220	252,525	284,859	318,376
5	188,294	218,382	253,139	289,180	326,423	365,051
6	212,315	246,419	285,836	326,727	369,000	412,864
7	259,967	302,039	350,700	401,213	453,463	507,713
Optimistic Scenario						
1	0	0	0	0	0	0
2	96960	111777	128,816	146,414	164,534	183,256
3	132,925	153755	177,771	202,630	228,281	254,841
4	164,844	191012	221220	252,525	284,859	318,376
5	188,294	218,382	253139	289,180	326,423	365,051
6	212,315	246,419	285836	326727	369,000	412,864
7	259,967	302,039	350,700	401213	453463	507713
Pessimistic Scenario						
1	0	0	0	0	0	0
2	96217	104137	112,889	121,553	130,095	138,490
3	131,801	142202	153,689	165,041	176,209	187,155
4	163,383	175,987	189901	203,638	217,137	230,347
5	186,584	200,807	216503	231993	247,204	262,078
6	210,351	226,231	243,753	261039	278004	294,581
7	257,499	276,668	297,812	318,660	339105	359062

[a] Numbers in the table correspond to one foot increments above a reference elevation. The elevation of the Red River for the same flood-event size changes at different locations within the city. The FSDFs were developed for portions of the city and combined using common reference elevations above and below the 100-year event.

Source: Adapted from U.S. Army Corps of Engineers (2000b).

Appendix Table D22. Projected Residential Damages for Flood-stage Damage Function, Breckenridge, by Population Scenario for Selected Years, 2006 through 2055

Elevation[a]	2006	2015	2025	2035	2045	2055
	-------------------	-------------------	-------------------	000s 2004 $	-------------------	-------------------
Baseline Scenario						
1	0	0	0	0	0	0
2	54,506	62,952	73,039	83,312	93,381	103,378
3	69,175	78,770	90,462	102,426	114,091	125,652
4	80,385	90,858	103,776	117,033	129,918	142,673
5	88,011	99,081	112,834	126,970	140,685	154,253
6	93,182	104,657	118,976	133,708	147,986	162,105
7	98,176	110,042	124,907	140,215	155,037	169,688
Optimistic Scenario						
1	0	0	0	0	0	0
2	54,718	65,189	77,612	90,576	103,930	115,672
3	69,485	82,053	97,173	113,087	129,574	143,695
4	80,771	94,940	112,121	130,289	149,171	165,110
5	88,448	103,707	122,291	141,992	162,502	179,678
6	93,654	109,653	129,187	149,928	171,543	189,557
7	98,682	115,394	135,846	157,592	180,273	199,097
Pessimistic Scenario						
1	0	0	0	0	0	0
2	54,506	62952	73,039	83,312	93,381	103,378
3	69,175	78,770	90462	102,426	114,091	125,652
4	80,385	90,858	103776	117,033	129,918	142,673
5	88,011	99,081	112,834	126970	140,685	154,253
6	93,182	104,657	118,976	133708	147986	162,105
7	98176	110042	124907	140215	155037	169688

[a] Numbers in the table correspond to one foot increments above a reference elevation. The elevation of the Red River for the same flood-event size changes at different locations within the city. The FSDFs were developed for portions of the city and combined using common reference elevations above and below the 100-year event.

Source: Adapted from U.S. Army Corps of Engineers (2000a).

Appendix Table D23. Projected Residential Damages for Flood-stage Damage Function, Drayton, by Population Scenario for Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	------------------	------------------	------------------ 000s 2004 $	------------------	------------------	------------------
	Baseline Scenario					
792.8	48	54	60	66	73	79
795.24	128	143	159	176	192	209
796.97	320	357	398	439	480	521
798.83	1,575	1,756	1,958	2,159	2,360	2,561
800.06	4,212	4,373	4,585	4,823	5,080	5,352
802.87	8,984	9,107	9,340	9,645	10,004	10,404
	Optimistic Scenario					
792.8	48	54	60	66	73	79
795.24	128	143	159	176	192	209
796.97	320	357	398	439	480	521
798.83	1,575	1,756	1,958	2,159	2,360	2,561
800.06	4,212	4,373	4,585	4,823	5,080	5,352
802.87	8,984	9,107	9,340	9,645	10,004	10,404
	Pessimistic Scenario					
792.8	48	54	60	66	73	79
795.24	128	143	159	176	192	209
796.97	320	357	398	439	480	521
798.83	1,575	1,756	1,958	2,159	2,360	2,561
800.06	4,194	4,205	4,266	4,360	4,476	4,603
802.87	8,934	8,637	8,444	8,344	8,305	8,298

Source: Adapted from U.S. Army Corps of Engineers (2004).

Appendix Table D24. Projected Residential Damages for Flood-stage Damage Function, Crookston, Baseline Population, Selected Years, 2006 through 2055

Elevation[a]	2006	2015	2025	2035	2045	2055
	-- 000s 2004 $					--
-13	0	0	0	0	0	0
-12	350	441	542	643	743	844
-11	540	680	835	991	1,146	1,302
-10	687	864	1,062	1,259	1,457	1,654
-9	1,180	1485	1824	2,164	2,503	2,842
-8	1,975	2487	3055	3,623	4,191	4,759
-7	2,511	3161	3883	4,605	5,327	6,049
-6	3,237	4075	5006	5,937	6,868	7,799
-5	4,216	5308	6520	7,733	8,946	10,158
-4	5,093	6411	7876	9,341	10,806	12,271
-3	6,120	7704	9464	11,224	12,985	14,745
-2	7,127	8972	11022	13,071	15,121	17,171
-1	8,174	10289	12640	14,991	17,342	19,693
0	9,461	11599	14035	16500	18,985	21,483
1	24,988	27404	30,856	34699	38,804	43,079
2	28,003	30473	34,124	38234	42,653	47,274
3	30,892	33414	37253	41620	46,341	51,292
4	33,174	35,736	39725	44294	49253	54466
5	35050	37646	41758	46493	51648	57076

[a] Numbers in the table correspond to one foot increments above a reference elevation. The elevation of the Red River for the same flood-event size changes at different locations within the city. The FSDFs were developed for portions of the city and combined using common reference elevations above and below the 100-year event.

Source: Adapted from U.S. Army Corps of Engineers (1997).

Appendix Table D25. Projected Residential Damages for Flood-stage Damage Function, Crookston, Optimistic Population, Selected Years, 2006 through 2055

Elevation[a]	2006	2015	2025	2035	2045	2055
	------------ 000s 2004 $ ------------					
-13	0	0	0	0	0	0
-12	350	441	542	643	743	844
-11	540	680	835	991	1,146	1,302
-10	687	864	1,062	1,259	1,457	1,654
-9	1,180	1485	1,824	2,164	2,503	2,842
-8	1,975	2487	3055	3,623	4,191	4,759
-7	2,511	3,161	3883	4,605	5,327	6,049
-6	3,237	4,075	5006	5,937	6,868	7,799
-5	4,216	5,308	6520	7,733	8,946	10,158
-4	5,093	6,411	7876	9,341	10,806	12,271
-3	6,120	7,704	9464	11224	12,985	14,745
-2	7,127	8,972	11,022	13071	15,121	17,171
-1	8,174	10,289	12,640	14991	17,342	19,693
0	9,470	11,678	14,177	16704	19249	21,808
1	25,108	28,435	32,719	37369	42259	47,322
2	28,145	31,690	36,321	41,383	46729	52278
3	31,055	34,808	39,771	45,228	51010	57026
4	33,353	37,270	42,496	48,265	54391	60775
5	35242	39295	44737	50,762	57172	63858

[a] Numbers in the table correspond to one foot increments above a reference elevation. The elevation of the Red River for the same flood-event size changes at different locations within the city. The FSDFs were developed for portions of the city and combined using common reference elevations above and below the 100-year event.

Source: Adapted from U.S. Army Corps of Engineers (1997).

Appendix Table D26. Projected Residential Damages for Flood-stage Damage Function, Crookston, Pessimistic Population, Selected Years, 2006 through 2055

Elevation[a]	2006	2015	2025	2035	2045	2055
	-- 000s 2004 $ --					
-13	0	0	0	0	0	0
-12	350	441	542	643	743	844
-11	540	680	835	991	1,146	1,302
-10	687	864	1,062	1,259	1,457	1,654
-9	1,180	1,485	1,824	2,164	2,503	2,842
-8	1,975	2,487	3,055	3,623	4,191	4,759
-7	2,511	3,161	3,883	4,605	5,327	6,049
-6	3,237	4,075	5,006	5,937	6,868	7,799
-5	4,216	5,308	6,520	7,733	8,946	10,158
-4	5,093	6,411	7,876	9,341	10,806	12,271
-3	6,120	7,704	9,464	11,224	12,985	14,745
-2	7,127	8,972	11,022	13,071	15,121	17,171
-1	8,174	10,289	12,640	14,991	17,342	19,693
0	9,457	11,569	13,976	16,415	18,873	21,343
1	24,948	27,012	30,087	33,595	37,348	41,250
2	27,956	30,012	33,217	36,932	40,937	45,116
3	30,838	32,885	36,215	40,129	44,374	48,820
4	33,115	35,154	38,582	42,654	47,089	51,745
5	34,987	37,020	40,529	44,730	49,322	54,151

[a] Numbers in the table correspond to one foot increments above a reference elevation. The elevation of the Red River for the same flood-event size changes at different locations within the city. The FSDFs were developed for portions of the city and combined using common reference elevations above and below the 100-year event.

Source: Adapted from U.S. Army Corps of Engineers (1997).

Appendix Table D27. Projected Commercial Damages for Flood-stage Damage Function, Fargo/Moorhead/Oakport Township, Baseline Population, Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	---------- 000s 2004 $ ----------					
894	0	0	0	0	0	0
895	4040	6040	8815	12,238	16,724	22,357
896	6376	9,532	13912	19,315	26,395	35,285
897	9515	14,226	20,762	28826	39,392	52,659
898	15937	23,827	34,774	48280	65979	88,199
899	27353	40,895	59,684	82,865	113242	151,380
900	50753	75,880	110,744	153,756	210120	280,884
901	99,618	148,936	217,368	301,792	412423	551,319
902	370228	553,518	807,843	1,121,602	1532760	2,048,964
903	615538	920,274	1,343,114	1,864,767	2548355	3,406,592
904	897470	1,341,782	1,958,293	2,718,875	3715563	4,966,893
905	1191346	1,781,148	2,599,535	3,609,170	4932222	6,593,300
906	1496571	2237481	3265541	4533846	6195866	8282516

Source: Adapted from U.S. Army Corps of Engineers (2005).

Appendix Table D28. Projected Commercial Damages for Flood-stage Damage Function, Fargo/Moorhead/Oakport Township, Optimistic Population, Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	---------- 000s 2004 $ ----------					
894	0	0	0	0	0	0
895	4,099	6747	10456	14,972	20,294	26,424
896	6,469	10,649	16502	23,629	32,030	41,703
897	9,654	15,892	24,628	35265	47,801	62,238
898	16,170	26,618	41,250	59,065	80,062	104,243
899	27,753	45,685	70,799	101,376	137415	178,916
900	51,495	84,768	131,368	188,102	254972	331,978
901	101,074	166,383	257,848	369,207	500459	651,605
902	375,640	618,359	958,285	1,372,146	1,859,942	2421673
903	624,536	1,028,079	1,593,238	2,281,320	3,092,326	4,026,255
904	910,588	1,498,964	2,322,979	3,326,220	4,508,686	5,870,377
905	1,208,759	1,989,799	3,083,638	4,415,389	5985053	7792629
906	1,518,446	2499589	3873671	5546620	7518434	9789115

Source: Adapted from U.S. Army Corps of Engineers (2005).

Appendix Table D29. Projected Commercial Damages for Flood-stage Damage Function, Fargo/Moorhead/Oakport Township, Pessimistic Population, Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	----------	----------	---------- 000s 2004 $	----------	----------	----------
894	0	0	0	0	0	0
895	4050	6119	8879	12123	15852	20,065
896	6393	9,658	14013	19,133	25,018	31,668
897	9,540	14,413	20913	28,554	37,337	47262
898	15,979	24,141	35,027	47825	62,536	79,159
899	27426	41,434	60,118	82084	107,333	135864
900	50,888	76,881	111,548	152,306	199,156	252096
901	99883	150,902	218,947	298,947	390902	494813
902	371214	560,823	813,709	1,111,028	1452778	1838960
903	617,177	932,419	1,352,867	1,847,187	2,415,378	3057441
904	899859	1,359,490	1,972,513	2,693,242	3,521,679	4457822
905	1194517	1,804,654	2,618,411	3,575,143	4,674,851	5917534
906	1500555	2267010	3289253	4491102	5872557	7433618

Source: Adapted from U.S. Army Corps of Engineers (2005).

Appendix Table D30. Projected Commercial Damages for Flood-stage Damage Function, Grafton, Baseline Population, Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	----------	----------	---------- 000s 2004 $	----------	----------	----------
820	0	0	0	0	0	0
821	13	16	18	20	22	23
822	37	42	49	55	59	64
823	61	71	82	91	99	107
824	112	130	150	167	181	195
825	569	657	761	848	916	990
826	1596	1,844	2,133	2,379	2,570	2777
827	2,718	3,141	3,633	4,051	4,378	4729
828	4667	5,393	6,239	6,956	7,517	8,119
829	6469	7,474	8,647	9,641	10,418	11253
830	9120	10,538	12,191	13,593	14688	15866
831	14283	16504	19093	21288	23004	24849

Source: Adapted from U.S. Army Corps of Engineers (2003).

Appendix Table D31. Projected Commercial Damages for Flood-stage Damage Function, Grafton, Optimistic Population, Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	---	---	000s 2004 $	---	---	
820	0	0	0	0	0	0
821	14	17	21	26	31	37
822	37	46	58	71	85	101
823	62	78	98	119	143	169
824	113	143	179	218	261	308
825	575	723	905	1106	1,325	1,563
826	1,613	2,028	2,538	3,102	3,717	4,385
827	2,746	3,453	4,323	5,282	6,330	7,468
828	4,715	5,929	7,423	9,070	10870	12,822
829	6535	8,218	10,288	12,571	15065	17772
830	9214	11,586	14,506	17,724	21241	25057
831	14431	18146	22718	27758	33266	39242

Source: Adapted from U.S. Army Corps of Engineers (2003).

Appendix Table D32. Projected Commercial Damages for Flood-stage Damage Function, Grafton, Commercial Damages, Optimistic Population, Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	---	---	000s 2004 $	---	---	
820	0	0	0	0	0	0
821	13	14	15	15	15	15
822	36	39	41	42	41	39
823	61	65	68	70	69	66
824	111	120	125	127	126	121
825	565	606	635	646	639	614
826	1,584	1,700	1,781	1,812	1,792	1,722
827	2,698	2,896	3,033	3085	3052	2,932
828	4,633	4,972	5,209	5,298	5,240	5,035
829	6,421	6,891	7,219	7,343	7,263	6978
830	9,054	9,716	10,178	10,353	10,240	9839
831	14,179	15217	15941	16214	16,037	15409

Source: Adapted from U.S. Army Corps of Engineers (2003).

Appendix Table D33. Projected Commercial Damages for Flood-stage Damage Function, Grand Forks/East Grand Forks, by Population Scenario for Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	--		000s 2004 $		--	
Baseline Scenario						
836.54	0	0	0	0	0	0
837.54	839,348	1202784	1683007	2252224	2923335	3715829
838.54	895,915	1,283,844	1,796,431	2,404,010	3,120,350	3966254
Optimistic Scenario						
836.54	0	0	0	0	0	0
837.54	844,058	1260274	1809412	2449788	3,181,403	4,004,257
838.54	900,942	1,345,209	1,931,356	2614890	3395811	4274120
Pessimistic Scenario						
836.54	0	0	0	0	0	0
837.54	834,779	1139047	1503769	1896541	2317362	2766232
838.54	891038	1215812	1605115	2024357	2473539	2952660

Source: Adapted from U.S. Army Corps of Engineers (1998).

Appendix Table D34. Projected Commercial Damages for Flood-stage Damage Function, Wahpeton, by Population Scenario for Selected Years, 2006 through 2055

Elevation[a]	2006	2015	2025	2035	2045	2055
	-- 000s 2004 $	---				
Baseline Scenario						
1	0	0	0	0	0	0
2	17877	23907	31350	39,572	48,573	58,400
3	30238	40,439	53028	66,936	82,161	98,783
4	46600	62,320	81,722	103154	126,618	152,234
5	63117	84,409	110,688	139717	171,497	206,192
6	81064	108,411	142,162	179,445	220262	264,823
7	98123	131,224	172,078	217207	266613	320,552
Optimistic Scenario						
1	0	0	0	0	0	0
2	17,877	23907	31,350	39,572	48,573	58400
3	30,238	40,439	53028	66936	82161	98,783
4	46600	62,320	81,722	103154	126,618	152234
5	63117	84,409	110,688	139,717	171497	206192
6	81064	108,411	142,162	179,445	220262	264823
7	98,123	131,224	172,078	217,207	266613	320552
Pessimistic Scenario						
1	0	0	0	0	0	0
2	17688	21571	25,644	29,461	33022	36328
3	29918	36488	43,376	49,832	55856	61448
4	46107	56,231	66,846	76796	86,079	94696
5	62450	76,161	90,540	104016	116,589	128261
6	80207	97,818	116,285	133,593	149742	164732
7	97086	118402	140,755	161705	181253	199398

[a] Numbers in the table correspond to one foot increments above a reference elevation. The elevation of the Red River for the same flood-event size changes at different locations within the city. The FSDFs were developed for portions of the city and combined using common reference elevations above and below the 100-year event.

Source: Adapted from U.S. Army Corps of Engineers (2000b).

Appendix Table D35. Projected Commercial Damages for Flood-stage Damage Function, Breckenridge, by Population Scenario for Selected Years, 2006 through 2055

Elevation[a]	2006	2015	2025	2035	2045	2055
	--- 000s 2004 $ ---					
Baseline Scenario						
1	0	0	0	0	0	0
2	28,419	37,053	45,412	52,376	57,726	61,865
3	34,121	44,487	54,524	62,886	69,309	74,278
4	38,659	50,404	61,776	71,249	78,527	84,157
5	39,865	51,977	63,703	73,473	80,978	86,783
6	46,037	60,024	73,566	84,848	93,515	100,219
7	48,915	63,776	78,164	90,151	99,360	106483
Optimistic Scenario						
1	0	0	0	0	0	0
2	28,610	39,804	52,450	65,314	78,397	88,766
3	34,350	47,791	62,974	78,419	94,127	106,577
4	38,919	54,147	71,349	88,849	106,646	120,751
5	40,134	55,837	73,576	91,622	109,974	124,519
6	46,347	64,481	84,967	105,807	127,000	143798
7	49,244	68,512	90,278	112,420	134,939	152786
Pessimistic Scenario						
1	0	0	0	0	0	0
2	28415	37,116	45,429	52,315	57,775	61,865
3	34117	44,563	54,544	62,812	69,367	74,278
4	38,654	50,490	61,798	71,166	78,593	84157
5	39,860	52,066	63,727	73,387	81,046	86783
6	46032	60,127	73,593	84,749	93,593	100219
7	48909	63,885	78,193	90,046	99,444	106483

[a] Numbers in the table correspond to one foot increments above a reference elevation. The elevation of the Red River for the same flood-event size changes at different locations within the city. The FSDFs were developed for portions of the city and combined using common reference elevations above and below the 100-year event.

Source: Adapted from U.S. Army Corps of Engineers (2000a).

Appendix Table D36. Projected Commercial Damages for Flood-stage Damage Function, Drayton, by Population Scenario for Selected Years, 2006 through 2055

Elevation	2006	2015	2025	2035	2045	2055
- (ft msl) -	--		000s 2004 $		--	
	Baseline Scenario					
792.8	37	37	37	37	37	37
795.24	97	97	97	97	97	97
796.97	242	242	242	242	242	242
798.83	1,191	1,191	1,191	1,191	1,191	1,191
800.06	2,948	2,948	2,948	2,948	2948	2,948
802.87	6,127	6,127	6,127	6,127	6,127	6127
	Optimistic Scenario					
792.8	37	37	37	37	37	37
795.24	97	97	97	97	97	97
796.97	242	242	242	242	242	242
798.83	1,191	1,191	1,191	1,191	1,191	1,191
800.06	2,948	2,948	2,948	2,948	2,948	2,948
802.87	6,127	6,127	6,127	6,127	6,127	6127
	Pessimistic Scenario					
792.8	36	34	32	29	27	24
795.24	96	91	84	78	71	64
796.97	241	226	210	194	177	161
798.83	1183	1,111	1,031	951	871	791
800.06	2,928	2,750	2,552	2,354	2,156	1958
802.87	6085	5,715	5,304	4,892	4,481	4070

[a] Elevation of Red River in mean sea level.

Source: Adapted from U.S. Army Corps of Engineers (2004).

Appendix Table D37. Projected Commercial Damages for Flood-stage Damage Function, Crookston, Baseline Population, Selected Years, 2006 through 2055

Elevation[a]	2006	2015	2025	2035	2045	2055
	------ 000s 2004 $ ------					
-9	0	0	0	0	0	0
-8	6	8	10	13	15	18
-7	16	21	27	34	40	47
-6	26	34	45	55	65	76
-5	32	43	55	68	81	95
-4	61	82	106	131	156	181
-3	139	187	241	296	353	411
-2	237	318	411	505	602	701
-1	377	504	651	801	954	1,112
0	649	870	1,123	1,381	1,645	1,917
1	1,956	2,620	3,382	4,159	4,957	5,774
2	2,902	3,886	5,017	6,169	7,352	8565
3	4,086	5,472	7,065	8,688	10,354	12061
4	5307	7,107	9,175	11,283	13,447	15664
5	6741	9,028	11,655	14,333	17,081	19898

[a] Numbers in the table correspond to one foot increments above a reference elevation. The elevation of the Red River for the same flood-event size changes at different locations within the city. The FSDFs were developed for portions of the city and combined using common reference elevations above and below the 100-year event.

Source: Adapted from U.S. Army Corps of Engineers (1997).

Appendix Table D38. Projected Commercial Damages for Flood-stage Damage Function, Crookston, Optimistic Population, Selected Years, 2006 through 2055

Elevation[a]	2006	2015	2025	2035	2045	2055
	---------- 000s 2004 $ ----------					
-9	0	0	0	0	0	0
-8	6	8	12	15	19	23
-7	16	23	31	40	50	62
-6	26	37	50	65	82	100
-5	32	46	63	82	102	125
-4	62	88	120	156	196	239
-3	140	199	273	354	444	542
-2	239	340	465	604	756	923
-1	379	539	737	957	1,200	1,465
0	654	929	1,271	1,651	2,069	2,525
1	1,970	2,798	3,828	4,972	6,232	7,606
2	2,922	4,151	5,678	7,376	9,244	11,283
3	4,115	5,845	7,996	10,386	13,017	15,889
4	5,345	7,591	10,384	13,489	16,906	20635
5	6,789	9,643	13,191	17,135	21,476	26213

[a] Numbers in the table correspond to one foot increments above a reference elevation. The elevation of the Red River for the same flood-event size changes at different locations within the city. The FSDFs were developed for portions of the city and combined using common reference elevations above and below the 100-year event.

Source: Adapted from U.S. Army Corps of Engineers (1997).

Appendix Table D39. Projected Commercial Damages for Flood-stage Damage Function, Crookston, Pessimistic Population, Selected Years, 2006 through 2055

Elevation[a]	2006	2015	2025	2035	2045	2055
	---------- 000s 2004 $ ----------					
-9	0	0	0	0	0	0
-8	6	8	10	12	14	15
-7	16	21	26	31	36	41
-6	26	34	42	50	59	66
-5	32	42	53	63	73	83
-4	61	80	101	120	140	158
-3	139	182	228	273	317	359
-2	237	310	389	465	540	612
-1	376	492	617	738	857	971
0	648	847	1,063	1,273	1,477	1,674
1	1,952	2,553	3,203	3,835	4,449	5,044
2	2,895	3,786	4,751	5,689	6,599	7,482
3	4,077	5,332	6,691	8,011	9,292	10,536
4	5,294	6,925	8,690	10,404	12,068	13,683
5	6,725	8,797	11,038	13,216	15,330	17,381

[a] Numbers in the table correspond to one foot increments above a reference elevation. The elevation of the Red River for the same flood-event size changes at different locations within the city. The FSDFs were developed for portions of the city and combined using common reference elevations above and below the 100-year event.

Source: Adapted from U.S. Army Corps of Engineers (1997).

APPENDIX E

Waffle Costs by Expense Category for Baseline, Optimistic, and Pessimistic Cost Scenarios

Appendix Table E1. Present Value of Waffle Costs, Baseline Projections, Full-scale Waffle, 2006 through 2055

	Acreage Option for Full-Scale Waffle		
Item	Minimum	Moderate	Maximum
Acreage	405,312	872,256	1,414,560
Sections	4,789	4,789	4,789
	----------------------- 000s $ -----------------------		
Enrollment Expenses	9,174	9,174	9,174
Retainer Payments	63,763	136,971	222,812
Landowner Payments (water storage payments)	68,205	146,511	238,331
Culvert Devices and Installation	43,599	43,599	43,599
Maintenance of Culvert Devices	13,458	13,458	13,458
Administration	9,732	12,478	15,666
Total	207,931	362,191	543,040
Cost per Year	4,159	7,244	10,861
Cost per Acre ($ per acre)	513	415	384

Appendix Table E2. Present Value of Waffle Costs, Baseline Projections, Half-scale Waffle, 2006 through 2055

	Acreage Option for Half-Scale Waffle		
Item	Minimum	Moderate	Maximum
Acreage	203,872	436,800	708,800
Sections	2,396	2,396	2,396
	----------------------- 000s $ -----------------------		
Enrollment Expenses	4,590	4,590	4,590
Retainer Payments	32,023	68,485	111,540
Landowner Payments (water storage payments)	34,254	73,255	119,309
Culvert Devices and Installation	21,815	21,815	21,815
Maintenance of Culvert Devices	6,734	6,734	6,734
Administration	8,548	9,918	11,517
Total	107,964	184,797	275,505
Cost per Year	2,159	3,670	5,510
Cost per Acre ($ per acre)	530	423	389

Appendix Table E3. Present Value of Waffle Costs, Optimistic Projections, Full-scale Waffle, 2006 through 2055

	Acreage Option for Full-Scale Waffle		
Item	Minimum	Moderate	Maximum
Acreage	405,312	872,256	1,414,560
Sections	4,789	4,789	4,789
	-----------------------	000s $	-----------------------
Enrollment Expenses	5,494	5,494	5,494
Retainer Payments	50,113	107,651	174,997
Landowner Payments (water storage payments)	47,860	102,812	167,131
Culvert Devices and Installation	39,697	39,697	39,697
Maintenance of Culvert Devices	5,838	5,838	5,838
Administration	6,737	8,045	9,564
Total	155,739	269,537	402,721
Cost per Year	3,115	5,391	8,054
Cost per Acre ($ per acre)	384	309	285

Appendix Table E4. Present Value of Waffle Costs, Optimistic Projections, Half-scale Waffle, 2006 through 2055

	Acreage Option for Half-Scale Waffle		
Item	Minimum	Moderate	Maximum
Acreage	203,872	436,800	708,800
Sections	2,396	2,396	2,396
	-----------------------	000s $	-----------------------
Enrollment Expenses	2,749	2,749	2,749
Retainer Payments	25,171	53,820	87,602
Landowner Payments (water storage payments)	24,039	51,400	83,664
Culvert Devices and Installation	19,862	19,862	19,862
Maintenance of Culvert Devices	2,921	2,921	2,921
Administration	6,173	6,826	7,588
Total	80,915	137,578	204,386
Cost per Year	1,618	2,752	4,088
Cost per Acre ($ per acre)	397	315	288

Appendix Table E5. Present Value of Waffle Costs, Pessimistic Projections, Full-scale Waffle, 2006 through 2055

	Acreage Option for Full-Scale Waffle		
Item	Minimum	Moderate	Maximum
Acreage	405,312	872,256	1,414,560
Sections	4,789	4,789	4,789
	-----------------------	000s $	-----------------------
Enrollment Expenses	14,099	14,099	14,099
Retainer Payments	77,863	1,675,253	272,253
Landowner Payments (water storage payments)	99,151	212,980	346,685
Culvert Devices and Installation	49,526	49,526	49,526
Maintenance of Culvert Devices	32,122	32,122	32,122
Administration	14,565	18,892	23,917
Total	287,326	494,872	738,602
Cost per Year	5,747	9,897	14,772
Cost per Acre ($ per acre)	709	567	522

Appendix Table E6. Present Value of Waffle Costs, Pessimistic Projections, Half-scale Waffle, 2006 through 2055

	Acreage Option for Half-Scale Waffle		
Item	Minimum	Moderate	Maximum
Acreage	203,872	436,800	708,800
Sections	2,396	2,396	2,396
	-----------------------	000s $	-----------------------
Enrollment Expenses	7,053	7,053	7,053
Retainer Payments	39,099	83,634	136,293
Landowner Payments (water storage payments)	49,789	106,499	173,555
Culvert Devices and Installation	24,781	24,781	24,781
Maintenance of Culvert Devices	16,073	16,073	16,073
Administration	12,699	14,857	17,377
Total	149,494	252,897	375,132
Cost per Year	2,990	5,058	7,503
Cost per Acre ($ per acre)	733	579	529

Appendix Table E7. Present Value of Waffle Costs, Full-scale Waffle, Baseline Cost Assumptions, Used Only for Events Larger than 100-year Floods, 2006 through 2055

	Acreage Option for Full-Scale Waffle		
Item	Minimum	Moderate	Maximum
Acreage	405,312	872,256	1,414,560
Sections	4,789	4,789	4,789
	----------------------- 000s $ -----------------------		
Enrollment Expenses	9,174	9,174	9,174
Retainer Payments	63,763	136,971	222,812
Landowner Payments (water storage payments)	7,428	15,957	25,957
Culvert Devices and Installation	43,599	43,599	43,599
Maintenance of Culvert Devices	13,458	13,458	13,458
Administration	9,732	12,478	15,666
Total	147,154	231,637	330,666
Cost per Year	2,943	4,633	6,613
Cost per Acre ($ per acre)	363	266	234

Appendix Table E8. Present Value of Waffle Costs, Half-scale Waffle, Baseline Cost Assumptions, Used Only for Events Larger than 100-year Floods, 2006 through 2055

	Acreage Option for Half-Scale Waffle		
Item	Minimum	Moderate	Maximum
Acreage	405,312	872,256	1,414,560
Sections	4,789	4,789	4,789
	----------------------- 000s $ -----------------------		
Enrollment Expenses	4,590	4,590	4,590
Retainer Payments	32,023	68,485	111,540
Landowner Payments (water storage payments)	3,731	7,978	12,994
Culvert Devices and Installation	21,815	21,815	21,815
Maintenance of Culvert Devices	6,734	6,734	6,734
Administration	8,548	9,918	11,517
Total	77,441	119,520	169,190
Cost per Year	1,549	2,390	3,384
Cost per Acre ($ per acre)	380	274	239

APPENDIX F

Documentation on Waffle Water Storage Procedures and Outcomes of Water Storage Scenarios on Crest Height Reductions

Evaluation of Waffle Storage Effects

One of the key pieces of information needed for the economic analysis was an evaluation of the Waffle effects for various magnitude floods, both smaller and larger than 1997. Although the effects of the conservative storage estimates on the 1997 flood were explicitly modeled using the Soil and Water Assessment Tool (SWAT) and the Hydrologic Engineering Center's River Analysis System (HEC-RAS), it was beyond the scope of the Waffle study to calibrate the models for a variety of hypothetical flood events. Thus, the modeling results alone did not provide sufficient information to evaluate the economic feasibility of a wide range of Waffle storage scenarios for various-sized flood events.

In order to quickly evaluate a variety of different storage and flood magnitude scenarios, an algorithm was developed based on the relationship between storage volume and peak flow reductions observed through the SWAT modeling effort. This relationship for a given watershed (i.e., U.S. Geological Survey 8-digit hydrologic cataloging unit) can be expressed by:

$$Y = 1.4638 + 4.6063 \cdot X + 2.8622 \cdot X^2 \qquad (R^2 = 0.84) \tag{1}$$

where Y is the peak reduction (%), and X is an independent variable.

Using $Q^{p}_{\text{pre-waffle}}$ and $Q^{p}_{\text{post-waffle}}$, in ft^3/sec, to signify the pre- and post-waffle peaks, respectively, Y is computed as:

$$Y = \frac{Q^{p}_{\text{pre-waffle}} - Q^{p}_{\text{post-waffle}}}{Q^{p}_{\text{pre-waffle}}} \times 100\% \tag{2}$$

X is formulated as:

$$X = \text{In}\left(\frac{V_{\text{waffle}}}{Q^{p}_{\text{pre-waffle}}} \right) \tag{3}$$

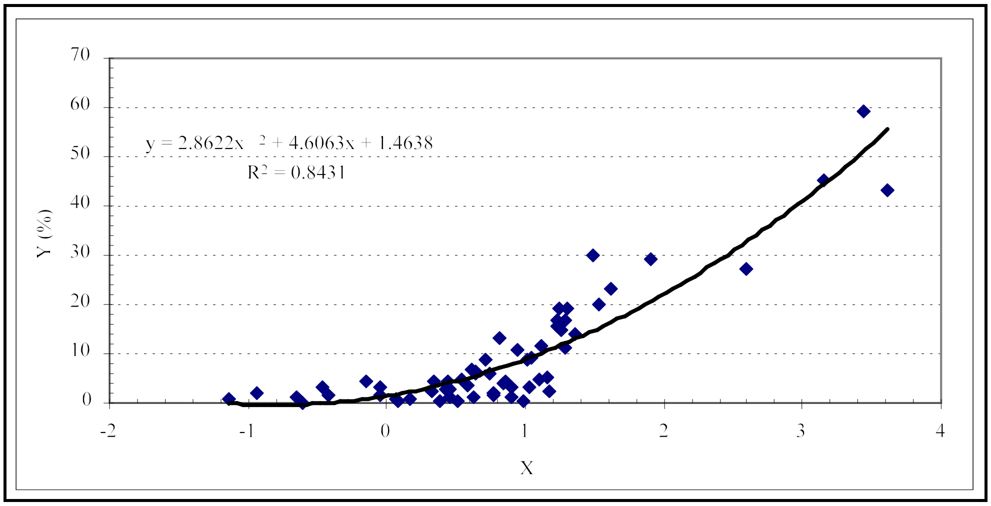
where V_{waffle} is the volume of waffle storage in the watershed (ac-ft).

The 95% confidence interval for Equation (1) is determined as:

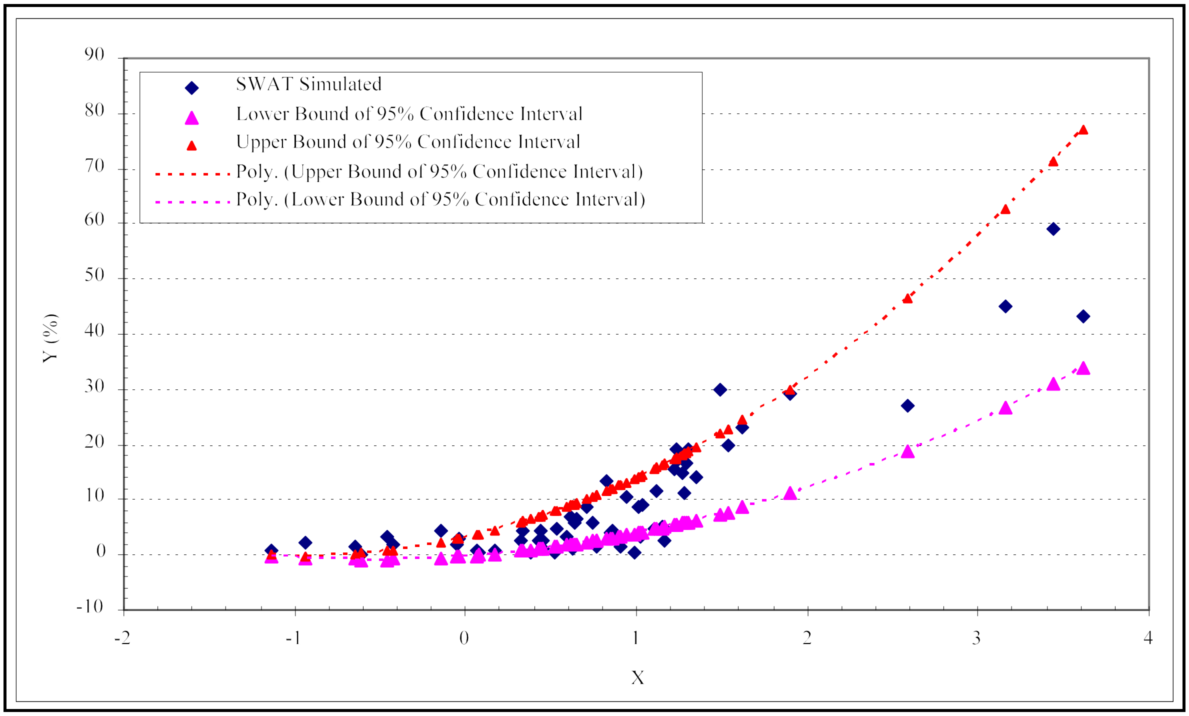
$$[-0.2659 + 2.1626 \cdot X + 2.0098 \cdot X^2, \qquad 3.1935 + 7.0500 \cdot X + 3.7146 \cdot X^2] \tag{4}$$

Prediction Accuracy

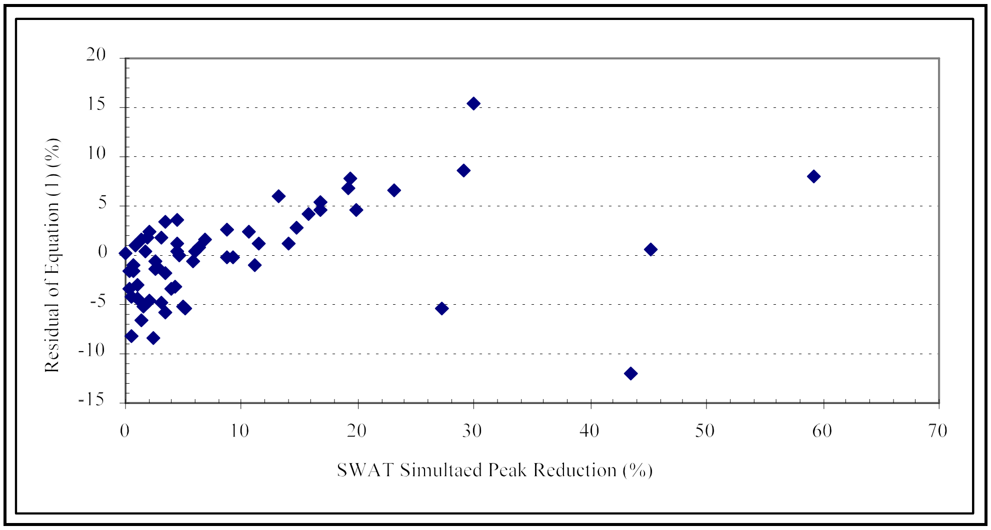
Equation (1) has a coefficient of determination (R^2) of 0.84, indicating a good prediction performance. Based on Figure 1, this equation can satisfactorily reflect the relationship between X and Y exhibited by the SWAT simulated data points (Figure 1). In addition, the statistical performance is verified by the fact that more than 62% of the data points fall in the 95% confidence interval computed using Equation (4) (Figure 2). Further, the prediction residuals from Equation (1) do not exhibit any clear pattern, i.e., the residuals do not have a consistent relationship with the SWAT simulated peak reductions (Figure 3). Therefore, Equation (1) may be a reliable model for use in estimating the peak reduction from a flood event with a peak discharge $Q^{p}_{pre\text{-}waffle}$ as a result of the waffle storage volume V_{waffle}.



Appendix Figure F1. SWAT Simulated Data Points and Regression Curve.



Appendix Figure F2. SWAT Simulated Data Points and 95 Percent Confidence Interval.



Appendix Figure F3. Pattern of Residuals.

Determination of Peak Reductions for Arbitrary Flood Events

Equation (1) was used to estimate the peak flow reduction for arbitrary flood events (e.g., flows twice as large as 1997), given various Waffle storage estimates for each watershed (moderate, conservative, etc…). For example, given that the 1997 peak discharge in the Rabbit River watershed was 6185 ft^3/sec, to approximate the flow reduction for a flood event

200% larger than 1997 (double the flows) if 100% of conservative Waffle storage estimates (22,784 ac-ft) were used, the following calculation was conducted:

$$X = 1\text{n}\left(\frac{22784}{2 \times 6185.00} \right) = 0.61078$$

$$\text{Y} = 1.4638 + 4.6063 \times 0.61078 + 2.8622 \times 0.61078^{2} = 5.3\ \%$$

Thus, a 5.3% reduction in peak flows would be expected at the mouth of the Rabbit River by implementing 100% of the Waffle storage determined from conservative volume estimates.

The validity of this approach can be evaluated by comparing the predicted reduction in flows estimated by the above methodology to the flows predicted using the SWAT models (Table 1). Since only the conservative storage estimates were explicitly modeled using SWAT, the moderate storage estimates could not be used for comparison. The results compare well for most of the watersheds; however, in the comparison of revised flows for 100% of the conservative storage volume estimates, five watersheds have % errors larger than 15% (no errors were larger than 25%). These five watersheds include the Upper Red, Marsh, Grand Marais, and Lower Red in Minnesota and the Lower Sheyenne in North Dakota. In the comparison of revised flows for 50% of the conservative storage estimates, two watersheds, the Grand Marais in Minnesota and the Bois de Sioux in North Dakota, have % errors greater than 15%. Although these errors are larger than the preferred range of ± 15%, the flow rates in the Upper Red and Grand Marais are so low after accounting for Waffle storage, that they have minimal impact on the flows within the Red River. The remaining four watersheds with errors larger than ± 15% for both storage scenarios have low to moderate flows, and, therefore, slightly larger errors in these systems should not overly impact the relative storage reduction results.

To estimate the reduced peak flows at various locations along the mainstem as a result of implementing Waffle storage, the adjusted flows from the tributaries upstream of various mainstem points were added together. Rating curves obtained from the USGS and USACE were then used to estimate the corresponding stage at each mainstem location. While this is not as accurate as using a hydraulic model, like HEC-RAS, to calculate the revised flows, it was sufficient for generating ballpark estimates. The effects of various Waffle storage estimates applied to floods smaller and larger than the 1997 flood (in terms of flows) were evaluated for Wahpeton/Breckenridge, Fargo/Moorhead, Grand Forks/East Grand Forks, and Drayton. (Tables 2 through 5).

Appendix Table F1. Comparison of Flow Reductions Predicted using the SWAT Models Versus the Empirical Equation Methods

			Revised Flows: 100% of Conservative Storage Estimates			Revised Flows: 50% of Conservative Storage Estimates		
	Watershed Name	USGS HUC	Equation-Predicted Flows (cfs)	SWAT-Predicted Flows (cfs)	% Error	Equation-Predicted Flows (cfs)	SWAT-Predicted Flows (cfs)	% Error
MN	Rabbit	9020101	5,422	5,000	-8.4	5,854	5,458	-7.3
	Mustinka	9020102	9,915	9,735	-1.8	9,915	9,830	-0.9
	Otter Tail	9020103	1,556	1,610	3.3	1,615	1,615	0.0
	Upper Red	9020104	611	510	-19.7	804	910	11.7
	Buffalo	9020106	8,006	8,575	6.6	8,477	8,640	1.9
	Marsh	9020107	6,750	5,540	-21.8	7,361	7,215	-2.0
	Wild Rice MN	9020108	10,139	10,095	-0.4	10,735	10,405	-3.2
	Sandhill	9020301	3,970	4,015	1.1	4,282	4,250	-0.7
	Red Lake	9020303	18,051	19,090	5.4	19,296	19,540	1.2
	Grand Marais	9020306	303	385	21.3	413	500	17.4
	Snake	9020309	14,480	13,835	-4.7	14,480	14,175	-2.2
	Lower Red	9020311	3,890	3,190	-21.9	3,890	3,480	-11.8
	Two Rivers	9020312	4,158	4,100	-1.4	4,501	4,445	-1.3
ND	Bois de Sioux	9020101	2,351	2,080	-13.0	2,428	2,090	-16.2
	Wild Rice	9020105	7,627	8,084	5.6	8,172	8,296	1.5
	Elm	9020107	3,880	3,460	-12.2	4,338	4,120	-5.3
	Goose	9020109	6,609	7,430	11.1	7,190	7,554	4.8
	Lower Sheyenne	9020204	3,907	4,708	17.0	4,324	4,747	8.9
	Maple	9020205	6,146	6,488	5.3	6,466	6,537	1.1
	Wilson	9020301	5,086	4,780	-6.4	5,471	5,477	0.1
	Turtle	9020307	2,095	2,168	3.4	2,213	2,207	-0.3
	Forest	9020308	2,790	2,768	-0.8	2,956	2,906	-1.7
	Park	9020310	6,498	6,286	-3.4	7,003	7,335	4.5
	Lower Red	9020311	2,928	2,770	-5.7	3,201	2,999	-6.7

Limitations and Empirical Adjustments

In the event that the equations, discussed above, are used in the future, it is worth mentioning some of the limitations of the approach and a correction factor used to account for attenuation of flows along the mainstem. For a location of interest along the mainstem, this procedure does not consider timing of the peaks from the corresponding contributing watersheds. In addition, between two adjacent locations (e.g., from Fargo to Halstad), the procedure assumes no attenuation of the peaks. These assumptions could result in either the overestimation or underprediction of the peak at the location of interest. To address this issue, a HEC-RAS model was used to evaluate the attenuation effects along the mainstem. The evaluation indicates that for the existing or pre-Waffle conditions, the attenuation effects are negligible for the 1997 flood. That is, the attenuation coefficients are close to a factor of “one”. For post-Waffle conditions, the attenuation effects for most reaches of the mainstem (i.e., from Fargo to Halstad, Halstad to Grand Forks, Grand Forks to Drayton, and Drayton to Emerson) were small; however, this was not the case with the reach between Wahpeton and Fargo/Moorhead. The attenuation coefficient for the reach from Wahpeton to Fargo/Moorhead was determined to be approximately 0.72 after implementation of 100% of conservative storage estimates, whereas, the coefficients for the other reaches were determined to be greater than 0.95. These attenuation effects would be a result of altered timing, friction along the river banks, and the width of the inundated flood plain. Therefore, it is recommended that the computed peaks at Fargo/Moorhead, using the equation approach, be multiplied by a coefficient of 0.72. Because attenuation effects along the other reaches were within a 5% margin of error, an attenuation coefficient was not applied to the other mainstem reaches.

The procedure described above was mainly designed to predict overall trends and relative changes between existing and post-Waffle conditions. It was used mainly to extrapolate the results for the 1997 flood to larger floods and to evaluate various Waffle storage volumes to provide a range of Waffle effects for use in the economic analysis. For those purposes, the procedure is sufficiently accurate. However, to more accurately predict “true” peak discharges along the mainstem, a hydraulic model such as HEC-RAS should be used.

Appendix Table F2. Estimated Red River Flow and Stage Reductions at Wahpeton as a Result of Various Waffle Storage Estimates

	50% of 1997 Flows (cfs) (Flow w/out storage: 10,072 cfs)		1997 Flows (cfs) (Flow w/out storage: 20,143 cfs)		125% of 1997 Flows (cfs) (Flow w/out storage: 25,179 cfs)		150% of 1997 Flows (cfs) (Flow w/out storage: 30,215 cfs)		200% of 1997 Flows (cfs) (Flow w/out storage: 40,286 cfs)	
	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction
Moderate Storage Estimates	7097	2.34	16430	1.92	21290	1.82	26222	1.66	36225	1.41
50% of Moderate Storage Estimate	8215	1.40	18113	1.02	23170	0.94	28394	0.75	38488	0.63
Conservative Storage Estimate	9056	0.73	19241	0.43	24319	0.40	29409	0.33	39625	0.23
50% of Conservative Storage Estimate	9622	0.31	19812	0.16	24894	0.12	29980	0.09	40286	0.0

Appendix Table F3. Estimated Red River Flow and Stage Reductions at Fargo as a Result of Various Waffle Storage Estimates

	50% of 1997 Flows (cfs) (Flow w/out storage: 14,961 cfs)		1997 Flows (cfs) (Flow w/out storage: 29,922 cfs)		125% of 1997 Flows (cfs) (Flow w/out storage: 37,402 cfs)		150% of 1997 Flows (cfs) (Flow w/out storage: 44,882 cfs)		200% of 1997 Flows (cfs) (Flow w/out storage: 59,843 cfs)	
	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction
Moderate Storage Estimates	6760	7.69	16117	6.18	21084	5.66	26153	4.75	36495	3.69
50% of Moderate Storage Estimate	8059	5.75	18247	5.13	23509	4.48	28924	3.69	39574	3.01
Conservative Storage Estimate	9124	4.52	19785	4.38	25164	3.75	30573	3.05	41455	2.59
50% of Conservative Storage Estimate	9894	3.81	20728	3.92	26165	3.37	31611	2.65	42673	2.42

Appendix Table F4. Estimated Red River Flow and Stage Reductions at Grand Forks as a Result of Various Waffle Storage Estimates

	50% of 1997 Flows (cfs) (Flow w/out storage: 55,769 cfs)		1997 Flows (cfs) (Flow w/out storage: 111,537 cfs)		125% of 1997 Flows (cfs) (Flow w/out storage: 139,421 cfs)		150% of 1997 Flows (cfs) (Flow w/out storage: 167,306 cfs)		200% of 1997 Flows (cfs) (Flow w/out storage: 223,074 cfs)	
	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction
Moderate Storage Estimates	31030	9.18	77665	4.97	102616	4.63	128211	3.43	180757	2.12
50% of Moderate Storage Estimate	38833	4.85	90378	2.97	117273	2.64	144723	1.58	200054	1.15
Conservative Storage Estimate	45189	2.54	100024	1.50	128057	1.28	156309	0.55	213457	0.48
50% of Conservative Storage Estimate	50014	1.21	106729	0.67	135400	0.46	163784	0.18	221140	0.10

Appendix Table F5. Estimated Red River Flow and Stage Reductions at Drayton as a Result of Various Waffle Storage Estimates

	50% of 1997 Flows (cfs) (Flow w/out storage: 69,646 cfs)		1997 Flows (cfs) (Flow w/out storage: 139,292 cfs)		125% of 1997 Flows (cfs) (Flow w/out storage: 174,115 cfs)		150% of 1997 Flows (cfs) (Flow w/out storage: 208,938 cfs)	
	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction	Reduced Flows	Stage Reduction
Moderate Storage Estimates	40269	3.73	99336	2.36	130842	2.11	163110	1.90
50% of Moderate Storage Estimate	49668	2.06	114617	1.39	148401	1.19	182803	1.06
Conservative Storage Estimate	57309	1.20	126067	0.70	161161	0.58	196425	0.50
50% of Conservative Storage Estimate	63097	0.61	133794	0.30	169484	0.22	204843	0.17

Note: The estimates for 200% of 1997 flows were not determined for this location because the flows far exceeded those on the USGS rating curve, and, therefore, accurate stage reductions could not be determined.

Appendix Table F6. Estimated Change in Crest Heights of Red River With the Waffle at Key Locations, by Waffle Scale, Flood Event Size, and Water Storage Scenarios

		Reduction in Red River Crest Heights (feet)			
Flood Event Size	Crest Height No Waffle	Conservative Water Storage		Moderate Water Storage	
		Half-scale	Full-scale	Half-scale	Full-scale
	------------------------------ Wahpeton/Breckenridge ------------------------------				
50% of 1997	17.54	0.31	0.73	1.40	2.34
1997	23.43	0.15	0.42	1.01	1.92
125% of 1997	25.8	0.13	0.40	0.94	1.83
150% of 1997	27.89	0.09	0.33	0.75	1.66
200% of 1997	31.56	0.00	0.23	0.63	1.42
	--------------------------------- Fargo/Moorhead ----------------------------------				
50% of 1997	33.01	3.82	4.52	5.75	7.69
1997	39.94	3.91	4.37	5.13	6.17
125% of 1997	41.87	3.37	3.76	4.48	5.67
150% of 1997	43.25	2.66	3.06	3.69	4.76
200% of 1997	45.35	2.41	2.59	3	3.68
	-------------------------- Grand Forks/East Grand Forks ---------------------------				
50% of 1997	45.22	1.21	2.54	4.86	9.19
1997	54.2	0.67	1.5	2.97	4.97
125% of 1997	57.61	0.46	1.28	2.64	4.62
150% of 1997	59.77	0.18	0.55	1.58	3.44
200% of 1997	62.55	0.09	0.48	1.15	2.11
	------------------------------------- Drayton --------------------------------------				
50% of 1997	42.63	0.61	1.2	2.05	3.72
1997	47.31	0.3	0.7	1.38	2.36
125% of 1997	48.96	0.22	0.58	1.19	2.11
150% of 1997	50.37	0.17	0.51	1.06	1.9
200% of 1997	na	na	na	na	na

Source: Kurz et al. (2007).

APPENDIX G

Gross Benefits by Location

Appendix Table G1. Present Value of Gross Benefits of the Waffle, by City, Waffle Scale, Water Storage Capacity, and Population Scenario, 2006 through 2055

Scale, Water Storage Estimate, and City	Population Scenario		
	Baseline	Optimistic	Pessimistic
	---------------------------- 000s $ ----------------------------		
Full-scale			
Moderate			
Fargo/Moorhead	729,478	826,239	715,666
Grand Forks/East Grand Forks	155,331	163,736	142,062
Wahpeton/Breckenridge	26,335	27,238	23,883
Drayton	3,647	3,647	3,408
Total	914,790	1,020,861	885,019
Conservative			
Fargo/Moorhead	621,817	704,135	610,059
Grand Forks/East Grand Forks	37,734	39,800	34,478
Wahpeton/Breckenridge	7,025	7,260	6,372
Drayton	1,651	1,651	1,536
Total	668,226	752,846	652,444
Half-scale			
Moderate			
Fargo/Moorhead	672,423	761,612	659,695
Grand Forks/East Grand Forks	120,687	127,235	110,355
Wahpeton/Breckenridge	15,780	16,313	14,309
Drayton	2,739	2,739	2,556
Total	811,629	907,900	786,914
Conservative			
Fargo/Moorhead	588,128	666,026	577,004
Grand Forks/East Grand Forks	14,139	14,912	12,921
Wahpeton/Breckenridge	2,491	2,575	2,264
Drayton	796	796	741
Total	605,554	684,309	592,929