Journal of Hydrology 511 (2014) 474–483

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Impact of subsurface drainage on streamflows in the Red River of the North basin

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ARTICLE INFO

Article history:
Received 25 September 2013
Received in revised form 21 January 2014
Accepted 28 January 2014
Available online 10 February 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Renduo Zhang, Associate Editor

Keywords:
Red River of the North
Streamflow response analysis
Subsurface drainage
SWAT

SUMMARY

The debate about subsurface drainage effects on streamflows has been reignited in the Red River of the North basin in North America, after a decades-long abnormally wet weather pattern in the region. Our study evaluated the applicability of the Soil and Water Assessment Tool (SWAT) in modeling subsurface drainage in a cold environment; we then employed streamflow response analyses to assess the potential impacts of the extensive subsurface drainage development in the Red River Valley (RRV) on streamflows in the Red River. The results showed that extensive subsurface drainage in the RRV would likely increase the magnitude of smaller peak flows while decreasing the magnitude of larger peak flows. Discharge reduction of large peak flows was mainly caused by reducing the flow volumes rather than increasing the time-to-peak of the hydrograph. Our analysis also suggested that extensive subsurface drainage could move more water from the watershed to the rivers in the fall season, creating more storage capacity in the soils. However, such increase in storage capacity in soils would have a negligible effect in reducing the monthly flow volumes in the following spring. The proposed method of coupling a watershed model with streamflow response analysis can be readily adopted by other researchers to evaluate the streamflow impact of land-use and climate changes around the world.

1. Introduction

The debate about effects of subsurface drainage on streamflows and associated environmental impacts among researchers and practitioners has a long tradition of more than 100 years (Robinson and Rycroft, 1999). The magnitude and direction of the effect of subsurface drainage on streamflows largely depend on a number of site-specific factors – soil properties, antecedent soil water storage, and climatic conditions, as well as many other factors such as topography, drainage system designs, drainage channels and networks, and tillage practices (Robinson, 1990; Skaggs et al., 1994; Robinson and Rycroft, 1999; Wiskow and van der Ploeg, 2003; Blann et al., 2009). The general agreement is that subsurface drainage would reduce peak outflows from waterlogged, clay-rich soils due to a change in the runoff generation mechanism from overland flow to subsurface drained flow in drained fields. Subsurface drainage increases infiltration in the clayey soils by reducing moisture content in the surface layers and lowering water table. On the other hand, subsurface drainage would increase peak flows when draining more permeable soils under typically dry antecedent conditions. In these cases, the drain lines create greater hydraulic gradients in the soils and thereby increase the peak subsurface flow rate.

However, the above findings about the hydrologic impact of subsurface drainage are generally drawn from the field-scale experiment and modeling studies conducted in humid regions of North America and Europe (Robinson and Rycroft, 1999; Tan et al., 2002). In contrast, only a few studies have originated from cold regions such as the Red River of the North basin (see the insert of Fig. 1; Jin and Sands, 2003; Jin et al., 2008, 2012), where agricultural drainage and late spring snowmelt flooding are two intertwined problems due to the flat topography and prevalence of poorly drained soils (Brun et al., 1981; Miller and Frink, 1984; Stoner et al., 1993; Jin et al., 2008).

In recent years, the debate about subsurface drainage effects on streamflows has been reignited in the Red River of the North (hereafter referred to as Red River) basin after a decades-long abnormally wet weather pattern in the region – the region received an equivalent of 2–3 years additional precipitation since the early 1990s (Jin et al., 2008). On one hand, high precipitation increased the magnitude and frequency of spring flood in the Red River. In

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http://dx.doi.org/10.1016/j.jhydrol.2014.01.070
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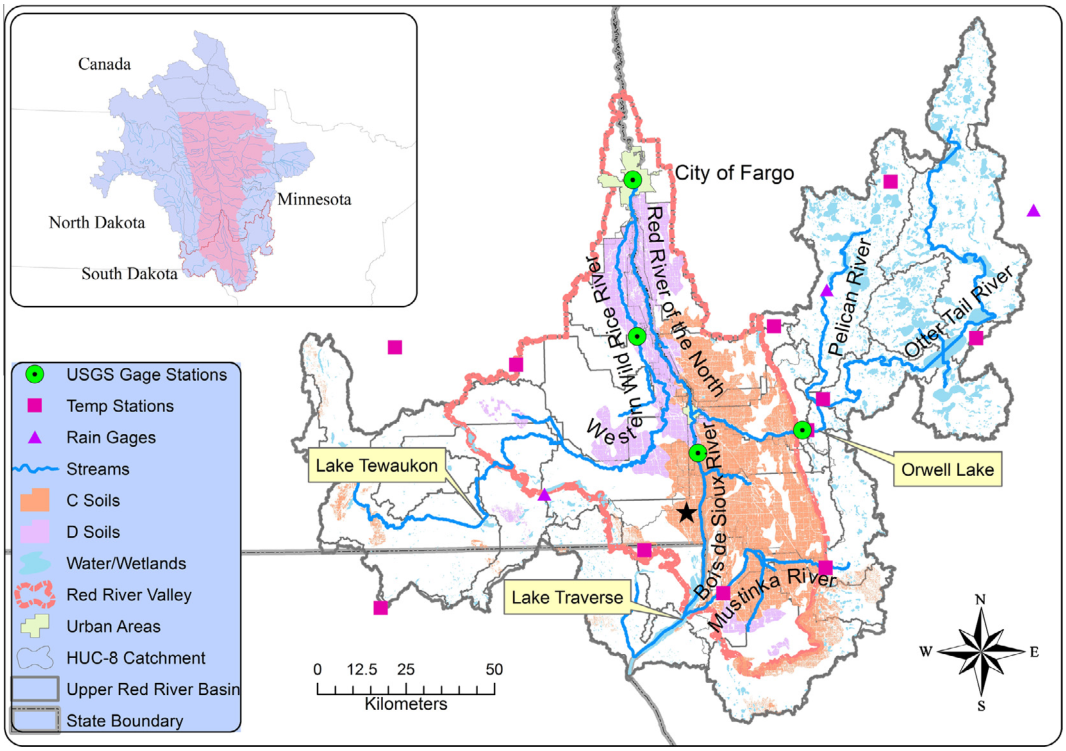

Fig. 1. The geophysical location of the upper Red River of the North basin with the star indicating the location of the Fairmount experimental site.

the century-long stream stage history at Fargo (Fig. 1), five out of the ten highest peak flows in the Red River occurred in the past 15 years (Lin et al., 2011) and the 50-year moving average of natural maximum flows increased from about 95 m^3/s (3400 ft^3/s) in 1950 to 225 m^3/s (8000 ft^3/s) currently (Foley, 2010). On the other hand, farmers in the Red River Valley (RRV) have been installing subsurface drainage systems, at an unprecedented pace, to move water more quickly from their fields in favor of early planting and higher crop yields (Pates, 2011). The center of the renewed debate is whether the expanded subsurface drainage in the RRV will increase or decrease the magnitude and frequency of spring flood in the Red River.

Since it is almost impossible to conduct field studies to evaluate the effects of subsurface drainage on streamflows at a basin scale, computer models are usually employed for such a purpose. In the literature, there are two approaches to applying computer models for impact analysis of subsurface drainage at the watershed scale. The first approach is to expand the applicability of a field-scale subsurface drainage model such as DRAINMOD to watershed-scale studies (Konyha et al., 1992; Northcott et al., 2002; Ale et al., 2012). In these studies, a watershed is usually divided into a number of small units that are modeled using the field-scale model, and then the simulated outflows from individual fields are routed through drainage channels and streams (Skaggs et al., 2003). This approach requires mapping individual drain lines in the watershed and representing spatial variation in drain spacing across the entire watershed. It can be prohibitive to obtain such detail information for a large watershed like the Red River basin. The second approach is to integrate subsurface drainage algorithms into watershed-scale hydrological models such as SWAT (Arnold et al., 1998), TOPMODEL (Beven and Kirkby, 1979), and MIKE-SHE (DHI, 2000), which were originally developed for modeling large, complex watershed systems (Carlier et al., 2007). These models have been widely tested in representing the spatial heterogeneity of a river basin in terms of soil properties, land use, topography, and climate, but they often use simplified algorithms in modeling subsurface drainage systems, discounting the variations of the spacing and size of tile drains (Moriasi et al., 2007). For example, subsurface drainage was incorporated as an additional term in mass balance equations in TOPMODEL or as an empirical water table height-drainage flow relationship in MIKE-SHE (Carlier et al., 2007). It is worth noting that, although watershed models can be used to evaluate the effects of subsurface drainage at the basin scale, the results cannot be always verified since the data for subsurface drainage are not readily available for large scales.

The tile drainage algorithms in SWAT have been refined over the years to improve the modeling of tile-drained watershed (Arnold et al., 1999; Du et al., 2005; Moriasi et al., 2007, 2009, 2012). First, excess water in the root zone is considered when estimating plant growth stress. When the soil approaches saturation, plants may suffer from aeration stress (Du et al., 2005). Second, to improve the prediction of water table depth, a restrictive soil layer is set at the bottom of the soil profile, allowing the soil profile above the restrictive layer to fill to saturation and additional water to fill the profile upward from the saturated bottom layers (Du et al., 2005; see also Moriasi et al., 2009). Third, the tile flow calculation equation has also been improved to include the difference between soil water content and field capacity (Neitsch et al., 2009). Finally, the latest releases of the SWAT model (SWAT2009 and SWAT2012) also incorporated the physically based Hooghoudt (1940) and Kirkham (1957) tile drain equations as an alternative method for tile flow simulation (Moriasi et al., 2012). SWAT2005 was evaluated favorably by Green et al. (2006) when employed to model the hydrology of the South Fork watershed in Iowa; about 80% of the watershed was tile drained. The same version of SWAT was also employed to model two tile-drained lowland catchments in Germany (Kiesel et al., 2010; Koch et al., 2013). The tile-drained areas ranged from 1.3% to 49.0%. To the best of our knowledge, the tile drainage algorithm of the SWAT model has never been successfully calibrated against daily tile flow observations collected from a 100% tile-drained field (see also Ahmad et al., 2002). Our research will fill this gap.

In addition, although SWAT has also been applied to model hydrology and water quality components in cold regions in the past by Benaman et al. (2005), Wang and Melesse (2005), Srivastava et al. (2006), Ahl et al. (2008), Chaponnière et al. (2008), Lévesque et al. (2008), Wang et al. (2008), Sexton et al. (2010), Flynn and Van Liew (2011), the SWAT model has never been applied to analyze the effects (i.e., magnitude and direction) of subsurface drainage on streamflows from a watershed where snowmelt hydrology is important in terms of streamflow generation in the spring. Therefore, the objective of our research is two-fold: (1) to evaluate the applicability of SWAT in modeling the hydrology of a 100% tile-drained watershed in a cold environment; and (2) to assess the implications of expanded subsurface drainage on the streamflows in the Red River basin in North America through the combined use of SWAT modeling and streamflow response analyses.

2. Materials and methods

2.1. Study area

The Red River basin is located near the geographic center of the North American continent. The river flows north and drains parts of the States of Minnesota, North Dakota, and South Dakota, as well as parts of the Provinces of Manitoba, and Saskatchewan, Canada (Stoner et al., 1993). Our study area is the upper Red River of the North basin (URRNB), a 17,000-square-km drainage area upstream to the US Geological Survey (USGS) stream gage station (#05054000) in the Red River located at the City of Fargo, North Dakota (Fig. 1). Like the greater Red River basin, the URRNB contains two distinct types of land forms – the flat plain and the rolling upland (refer to Fig. 1). The center area, termed the Red River Valley, is remarkably flat and was the bottom of glacial Lake Agassiz. The lake deposits, consisting of sorted and stratified clay and silt, are as much as ~30 m thick. Extending east and west of the central plain are the gently rolling uplands, dotted with prairie potholes and depressions. The glacial drift in the uplands consists of an unsorted and unstratified mixture of clay, silt, sand, and gravel, commonly referred to as till (Miller and Frink, 1984; Stoner et al., 1993).

The major landuses in the URRNB are row crop agriculture (65%), followed by pasture/hay (11%), water/wetlands (10%), forest (9%), and urban (5.0%). The region is under the influence of continental climate with cold winters and moderately warm summers. Mean annual precipitation in the basin is about 500 mm and about three-fourths falls from April through September, and December through February are usually the driest months. The growing season runs from the middle of May through the middle of September, ranging from 100 to 140 days (Stoner et al., 1993).

As mentioned above, the basin experiences two types of water problems – excess water on farmlands and stream bank overflows. The first problem is the ponded water in shallow depressions and the large amount of free water held internally in the soil due to slow percolation or high water tables. Under natural conditions, the localized excess water is removed by seepage and evaporation, which may be too prolonged to permit efficient use of the land for crops. Therefore, artificial drainage is often used to solve this problem. For the second problem, the maximum discharges of the year commonly occur in late March or in April, following the spring snowmelt runoff. It is self-evident that the northward-flowing, meandering Red River with a gentle slope (0.04–0.25 m/km) is prone to spring flooding.

2.2. The SWAT model

The SWAT model is a continuous, physically-based, semi-distributed watershed model that was originally developed by the USDA Agricultural Research Service to assess the impact of agricultural land use management practices on water, sediment, and nutrient yields in large basins with different soil types, land uses, and management practices (Arnold et al., 1998). The SWAT model divides a watershed into a number of subbasins connected by stream networks. Each subbasin is further divided into a number of hydrologic response units (HRUs) that are unique combinations of different land uses, soils, and surface slopes. Within each subbasin the areas with similar land use, soil types, and surface slopes are lumped together into a single HRU and the different HRUs within a subbasin are not spatially distributed. Such HRU delineation is to minimize the computational cost of modeling large basins (Zhang et al., 2008).

The processes associated with water movement in a watershed include snowmelt and sublimation, infiltration, evaporation, plant uptake, lateral and tile flows, percolation, ground-water flow, and channel routing (Neitsch et al., 2009). SWAT2009 is employed in our study. It is worth mentioning that SWAT2009 uses the simple temperature-index algorithm (Hock, 2003) to calculate the snowmelt processes for regions with small elevation changes and the temperature-index plus elevation band algorithm for mountainous terrains (Fontaine et al., 2002). When properly calibrated, the temperature-index methods often outperform energy balance models; yet require much less input data than the latter (Hock, 2003; Zhang et al., 2008).

Like SWAT2005, SWAT2009 uses Eq. (1) to estimate the daily drained water flow from soil profile above the tile drains (Neitsch et al., 2009).

$$tile_{wtr} = \left(\frac{h_{wtbl} - h_{drain}}{h_{wtbl}}\right)(SW - FC)\left(1 - exp\left[\frac{-24}{tile_{drain}}\right]\right),\ \text{if } h_{wtbl} > h_{drain} \quad (1)$$

where $tile_{wtr}$ is the tile drained water (mm) removed from the soil profile on a given day; SW is the soil water content (mm), FC is field capacity (mm); h_{wtbl} and h_{drain} are heights (mm) of water table and tile drain above an impervious layer, respectively; and $tile_{drain}$ is the time (hrs) to drain the soil to FC. The tile drained water estimated by Eq. (1) for individual HRUs is then aggregated to obtain the tile flow for a subbasin, Q'_{tile}, which is subsequently routed to the main channel by Eq. (2):

$$Q_{tile} = (Q'_{tile} + Q_{tilestor,i-1})\left[1 - exp\left(\frac{-1}{TT_{tile}}\right)\right] \quad (2)$$

where Q_{tile} is the amount of tile flow (mm) discharging into the main channel on a given day; Q'_{tile} is the amount of tile flow (mm) generated from the soil profile within a subbasin on a given day; $Q_{tilestor,i-1}$ is the amount of the lagged tile flow (mm) from the previous day; and TT_{tile} is the travel time (days) of tile flow to reach the main channel, which is calculated according to Eq. (3).

$$TT_{tile} = \frac{tile_{lag}}{24} \quad (3)$$

where $tile_{lag}$ is the lag time (hrs) for a tile drain.

2.2.1. The SWAT model for the Upper Red River of the North basin

A watershed-scale SWAT model was developed for the entire URRNB based on the following datasets. Watershed delineation was based on the 5-meter LiDAR-based DEM provided by the International Water Institute (http://www.iwinst.org/). The stream networks, surface water bodies and wetlands were extracted from the National Hydrography Datasets (http://www.horizon-systems.com/nhdplus/HSC-wth09.php). Three major reservoirs are located at the three tributaries of the Red River. Lake Traverse, formed by the White Rock dam, is located in the Bois de Sioux River; Lake Tewaukon, formed by the North Bay dam, is located in the

Western Wild Rice River; and Orwell Lake, formed by the Orwell dam, is located in the Otter Tail River (Fig. 1). The first two reservoirs were parameterized based on the observed streamflows obtained from the downstream USGS gage stations and the third one was parameterized based on the US Army Corps of Engineers' reservoir database (http://www.mvp-wc.usace.army.mil). If a subbasin contains more than 5% of its area as open water body, excluding the river within the subbasin, a wetland was included in the subbasin. The State Soil Geographic (STATSGO) database and the National Land Cover Dataset 2006 (NLCD 2006) were used for soil and land use classifications. But, the single row crop class in NLCD 2006 was split into corn and soybean based on the National Agricultural Statistics Service's (NASS) Crop Data Layer for the year of 2006. Soybean and corn are two major crops, representing 49% and 34% of row crops, respectively, in the basin in 2006. Daily precipitation and daily minimum and maximum temperature were retrieved from 12 Cooperative Observer Network's weather stations of the National Oceanic and Atmospheric Administration within or around the study area (Fig. 1).

Within the watershed-scale SWAT model, an HRU was set up for a 20-ha subsurface drainage experiment field located near Fairmount in Richland County, ND (Fig. 1). Tile flow recordings from the 100% tile-drained field were collected for 2008–2010 when corn was grown in 2008–2009 and soybean was grown in 2010 in the field. The two major soil types are Clearwater-Reis silty clay and Antler-Mustinka silty clay loam. A detailed description of the field and the experiment is provided in Jia et al. (2012).

2.3. Model calibration strategy and evaluation metrics

The watershed-scale SWAT model for the URRNB was calibrated against daily streamflows and monthly flow volumes observed at the four USGS stream gage stations (Fig. 1) to develop the values for the parameters that govern various hydrologic processes in the SWAT model, except for subsurface drainage. The calibration period is 1993–2000 and the validation period is 2001–2010. The parameters associated with subsurface drainage systems were calibrated using tile flow daily observations in 2008–2010 at the Fairmount tiled field. The calibrated values for the subsurface drainage parameters found for the experimental tiled field were then transferred to the other existing tiled areas of the URRNB. The calibrated hydrologic and subsurface drainage parameters and their values are listed in Table 1. Finally, the calibrated watershed-scale SWAT model was used for streamflow impact analysis under the expanded tiling scenario in the URRNB.

The SWAT model's performance was evaluated by graphical comparison and two indicators, namely, Nash–Sutcliffe efficiency (*NSE*; Nash and Sutcliffe, 1970), and percent of bias (*PBIAS*; Gupta et al., 1999). The *NSE* is the measure of how closely the model-simulated values match with the observed values. It is calculated as

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right] \tag{4}$$

where O_i and S_i are the ith observed and predicted streamflows, respectively; $\bar{O}$ is the average of the observed streamflows; and n is the number of observations. The *NSE* takes a value from $-\infty$ to 1, with greater values indicating better agreement. *PBIAS* indicates the average tendency of over- or under-prediction by a model. It is calculated as

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n}O_i}\right] \times 100 \tag{5}$$

where the symbols are defined as the same as in Eq. (4).

2.4. Expanded tiling and climate scenarios

It is reasonable to assume that the potential locations of tile-drained fields will be located where row crops are grown which are on flat lands with poorly drained, clay soils (Northcott et al., 2002; Varner et al., 2002; Sugg, 2007; Naz and Bowling, 2008; Srinivasan et al., 2010). By definition, the hydrologic group D soils are poorly drained, clay-rich soils and often indicate the existence of a shallow groundwater table (USDA-NRCS, 2009). To estimate the locations and areas of the potential tile-drained fields in the URRNB, we first overlaid the soil, land use, and surface slope (derived from DEM) data layers. For example, if a spatial unit is under hydrologic group D soil, having row crop for land use and a surface slope of 1% or less, then the spatial unit could potentially be tile-drained. It is evident that, in the URRNB, a high percentage of the existing subsurface drainage systems are actually installed in fields with hydrologic group C (permeable) soil (Jia and Scherer, 2011; personal communication). Therefore, we included both C and D soils in the process of estimating the locations and areas of the potentially tile-drained fields. The potentially tile-drained area, denoted as "Expanded scenario", was about 16.8% of the entire URRNB. Based on the county-level subsurface drainage records (Sugg, 2007; Schuh, 2008), the existing tiled area, denoted as "Existing scenario", was estimated to be 120 km^2 in the URRNB, about 0.7% of the total basin area. Some existing tiled fields, such as the 20-ha Fairmount experimental field located in Richland County, ND, are found in hydrologic group C soils. The areas of the existing tiled fields and the potentially-tiled fields and their distribution among subbasins in the SWAT model are listed in Table 2.

In terms of climate scenario in the future, we simply assume the climate condition will be exactly the same as in the past two decades (i.e., from 1993 to 2010) when conducting the following streamflow impact analysis under the expanded subsurface drainage scenario.

2.5. Streamflow response analysis

Three hydrologic analyses – flood-frequency analysis, normalized-hydrography analysis, and seasonal streamflow analysis – were conducted in an attempt to identify any significant changes in streamflow response due to potential increases in subsurface drainage in the Red River basin. The USGS stream gage station at Fargo, North Dakota, was selected as the point of interest for analysis. The purpose of the flood-frequency analysis was to identify if there are any changes in the magnitude and the frequency of annual peak flows in the Red River at Fargo under the expanded tiling scenario in the basin. We compared the annual peak-flow frequency curves of the Red River at Fargo during a 20-year period under the existing and the expanded subsurface scenarios. The annual peak flow-frequency analysis was conducted using a freeware MATLAB® function – b17 (Burkey, 2009) based on a log-Pearson Type III distribution following the guidelines specified in the Bulletin #17B (USGS, 1982) for determining flood flow frequency.

The normalized-hydrography analysis was done to evaluate possible changes in the shape of the hydrograph, particularly during spring snowmelt time, in the Red River at Fargo caused by subsurface drainage. Although it is generally believed that subsurface drainage in RRV decreases the speed at which the excess water moves out of the *field*, the hydrographs of the Red River at Fargo may have a shorter or longer duration depending on the spatial locations of the tile-drained fields in the *basin* (Miller and Frink, 1984; Anderson and Kean, 2004). If subsurface drainage is to reduce the duration of the hydrographs of the Red River at Fargo, resulting higher peak flows, the averaged normalized-hydrograph

Table 1
SWAT parameters governing hydrologic processes and subsurface drainage.

Name	Description (unit)	Default values	Calibrated values
Basin-level parameters			
SFTMP	Snowfall temperature (°C)	1.00	0.00
SMTMP	Snowmelt temperature (°C)	0.50	1.50
TIMP	Snowpack temperature lag factor	1.00	0.20
SURLAG	Surface runoff lag coefficient (day)	4.00	0.20
HRU-level parameters			
DEP_IMP[a]	Depth of impervious layer (mm)	–	1250
DDRAIN[a]	Depth to subsurface drain (mm)	900	1180
TDRAIN[a]	Time to drain soil to field capacity (hrs)	48	48
GDRAIN[a]	Drain tile lag time (hrs)	96	168
CN2	Curve number	31–92	30–97
SOL_AWC	Available water capacity of soil (mm/mm)	0.08–0.24	0.01–0.24
ESCO	Soil evaporation compensation factor	0.00	1.00
EPCO	Plant uptake compensation factor	0.00	1.00
GW_SPYLD	Specific yield of shallow aquifer (m^3/m^3)	0.003	0.30
ALPHA_BF	Baseflow factor (days)	0.048	0.50
GW_DELAY	Groundwater delay (days)	31	5–31
SHALLST	Initial depth of water in shallow aquifer (mm)	0.5	1000
Reservoir parameters			
RES_PVOL	Volume at principal spillway (10^4 m^3)	–	300–405
RES_EVOL	Volume at emergency spillway (10^4 m^3)	–	427–800
RES_PSA	Surface area at principal spillway (ha)	–	135–700
RES_ESA	Surface area at emergency spillway (ha)	–	135–1000
RES_K	Hydraulic conductivity at bottom (mm/hr)	–	0.8–1.0
Wetland parameters			
WET_FR	Fraction of subbasin area drained into wetlands	–	0.10–0.50
WET_NVOL	Volume of water at normal water level (10^4 m^3)	–	1100–3500
WET_MXVOL	Volume of water at maximum water level (10^4 m^3)	–	2000–14,250
WET_NSA	Surface area at normal water level (ha)	–	2000–7000
WET_MXSA	Surface area at maximum water level (ha)	–	2200–21,500
WET_K	Hydraulic conductivity of bottom (mm/hr)	–	0.5–433.0

[a] Subsurface drainage parameters were calibrated at the field scale.

Table 2
Tile-drained areas and their spatial distributions in the URRNB under different tiling scenarios.

Streams (HUC-8 catchment)	Total drainage area (km^2)	Existing scenario		Expanded scenario	
		Total tiled area (km^2)	Tiling percentage (%)	Total tiled area (km^2)	Tiling percentage (%)
Mustinka River	2228	34.7	1.6	594.2	26.7
Bois de Sioux River	2875	11.6	0.4	837.9	29.1
Western Wild Rice River	5788	26.5	0.5	665.6	11.5
Otter Tail River	4947	14.7	0.3	212.5	4.3
Upper Red River	1060	29.8	2.8	536.2	50.6
Total or average	16,898	117.3	0.7	2846.4	16.8

under a tiled scenario would have steeper rising and falling limbs than that under the existing scenario, or vice versa.

In the normalized-hydrography analysis, hydrographs were chosen by inspection to remove those hydrographs from the analysis that did not provide a useful characterization of a simple runoff-hydrograph shape. The following criteria adapted from Miller and Frink (1984), to which the details of the method should be referred to, were used to select the hydrographs of the Red River at Fargo:

1. Resulted from a snowmelt-runoff event.
2. Included only one main peak.
3. Peak discharge greater than approximately 110 m^3/s (about 4000 ft^3/s).
4. Complete daily record for the 41-day period.
5. No other complications in the shape.

Based on the above criteria, ten hydrographs (Table 3) were chosen from the model-simulated daily streamflows in Red River at Fargo. Then the selected hydrographs were normalized so that they could be readily compared even though each individual daily discharge was different. The normalization was done by including the discharge values for 15 days before and 25 days after each hydrograph peak. Each ordinate on the hydrograph was then divided by the peak discharge value. This resulted in normalized-hydrograph ordinates to vary between 0 and 1 and hydrograph

Table 3
Years from which snowmelt-runoff hydrographs for the Red River at Fargo were chosen to be included in the normalized-hydrograph analysis.

Year	Hydrograph duration
1993	3/19 to 4/28
1996	3/31 to 5/10
1997	3/25 to 5/4
1998	3/22 to 5/1
1999	3/25 to 5/4
2001	3/26 to 5/5
2005	2/26 to 4/7
2006	3/22 to 5/1
2007	3/26 to 5/5
2009	3/31 to 5/10
Total number of years	10

durations to be 41 days. For all normalized-hydrographs the peak discharges occur on the 16th day.

Finally, the seasonal impact of subsurface drainage on streamflows in the Red River was evaluated through examining the changes of the average monthly flow volume during a 20-year period under the two different scenarios (existing vs. expanded).

3. Results and discussion

3.1. Model calibration and parameter estimation

3.1.1. Subsurface drainage parameter estimation at the field scale

As shown in Eqs. (1)–(3) and in Table 1, SWAT's subsurface drainage process is governed by four parameters: the depth of impervious layer (DEM_IMP), the depth to subsurface tile drain (DDRAIN), the time to drain the soil to field capacity (TDRAIN), and the drain tile lag time (GDRAIN). While the value of DDRAIN was fixed at the depth of the drain tiles in the study site (i.e., 1180 mm), the three remaining subsurface drainage parameters were determined by comparing the simulated tile flow from the HRU, which was set up to model the 20 ha Fairmount field, against the observed daily tile flow from 2008 to 2010. The graphical comparison of the simulated and observed daily tile flows of the Fairmount field is shown in Fig. 2 with *NSE* being equal to 0.5 and *PBIAS* being −1.4%.

Fig. 2 shows that the simulated tile flow largely captured the pattern of the observed tile flow – significant tile flows observed during spring and fall seasons and no measurable tile flows observed during the growing seasons. It should be noted that we did not have observed data to verify the simulated peak flow occurring in the mid-June of 2010, which was presumably triggered by a significant rainfall event (51 mm) on June 15, 2010. It should also be noted that, during the spring of 2009, the onset of the model-simulated tile flow was about two weeks earlier than that of the observed tile flow. The RRV region was fighting a historic spring flood during that time and the farmers were asked to turn off their lift stations at the outlet of the drainage system before the Red River crested.

Table 4 compares the SWAT-simulated hydrologic components (except for precipitation) in the Fairmount field during 2008–2010 with or without tile drains installed. All components are average values over the three-year simulation period. First, the average surface runoff decreased about 30% by tiling the field; whereas the water yield, which is the sum of surface and subsurface runoffs (i.e., lateral, tile flows, and groundwater flow), increased about 10% during the same period. Second, the average soil water content (SWC) decreased about 10% by tiling the field; but the tiling did not make much difference in evapotranspiration (ET) and the slight decrease in ET was likely due to the decrease in SWC. Third, when the field was tiled, the tile flow accounted for about 16% of the annual precipitation or about 37% of the water yield. This was in general agreement with the findings from field studies in the Midwest of United States, in which 8–27% of annual precipitation was reportedly converted to tile flow in the tiled fields in the states of Minnesota (Jin and Sands, 2003; Sands et al., 2008) and Indiana (Kladivko et al, 2004).

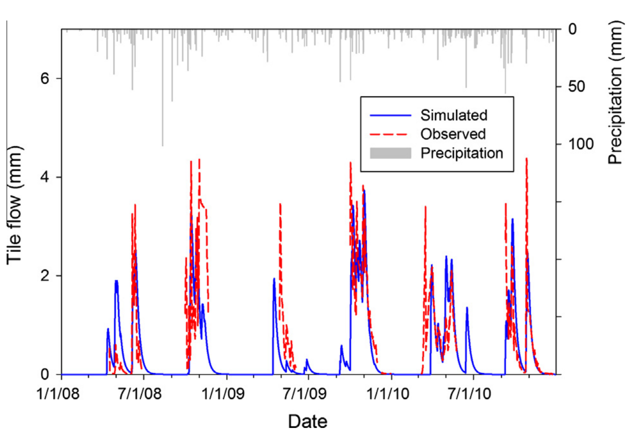

Fig. 2. Graphical comparison of simulated and observed daily tile flows at the Fairmount study field.

Table 4
Simulated changes in hydrologic components due to subsurface drainage in the tile-drained field (2008–2010).

Hydrologic components	Without tile (mm)	With tile (mm)	Change (mm)
Precipitation	755	755	0
Evapotranspiration	422	418	−4
Surface runoff	297	209	−88
Subsurface flows[a]	2	121	119
Water yield (surface runoff + subsurface flows)	299	330	31
Soil water content	247	214	−33

[a] Subsurface flows include lateral flow, tile flow and active groundwater flow.

3.1.2. SWAT model evaluation at the watershed scale

Once the subsurface drainage related parameters were calibrated against the field data, other hydrology parameters (listed in Table 1) were calibrated at the watershed scale against the daily streamflow observations at the four USGS gage stations in the URRNB (shown in Fig. 1), which include the stations in the Red River at Fargo, ND (#05054000), the Otter Tail River below Orwell Dam near Fergus Falls, MN (#05046000), the Bois de Sioux River near Doran, MN (#05051300), and the Wild Rice River near Abercrombie, ND (#05053000). The graphical comparisons of the model-simulated and observed daily streamflows and monthly volumes at these USGS gage stations are shown in Figs. 3 and 4 and the statistics for the model's performance are listed in Table 5.

In general, the SWAT model's performance is satisfactory in terms of simulating daily streamflows and monthly volumes at the four USGS gage stations during the calibration period (1993–2000) and validation period (2001–2010). Comparatively, the SWAT model did better in modeling the streamflows of the Red River and the Otter Tail River than those of the Bois de Sioux River and the Wild Rice River in North Dakota, mainly because little information was available about the reservoir releases for Lake Traverse in the Bois de Sioux River and for Lake Tewaukon in the Wild Rice River. On average, the model under-predicted streamflows for the Otter Tail River while over-predicting streamflows for the other three streams (see Table 5).

Our results of model calibration and validation are comparable to those studies where SWAT2005 was used to simulate the streamflows from partially tile-drained watershed (Green et al., 2006; Kiesel et al., 2010; Koch et al., 2013). When SWAT was used to model the streamflows from an 80% tiled watershed in Iowa (Green et al., 2006), NSEs were 0.2–0.5 for daily streamflow calibration and validation and 0.5–0.9 for monthly streamflow calibration and validation. When incorporating both tile drainage and landscape depressions in their SWAT model for a 31% tiled watershed in the lowland area of Germany, Kiesel et al. (2010) found that NSEs of daily streamflow comparison improved from 0.65–0.72 to 0.78. When Koch et al. (2013) applying SWAT to model a tile-drained lowland catchment (0.3-31.9% tiled) in Germany, their NSEs of streamflow comparison ranged from 0.22 to 0.81 for calibration and from −0.81 to 0.66 for validation.

Although the SWAT model did very well in modeling the peak flows in the historic spring flood in 1997, the model generally

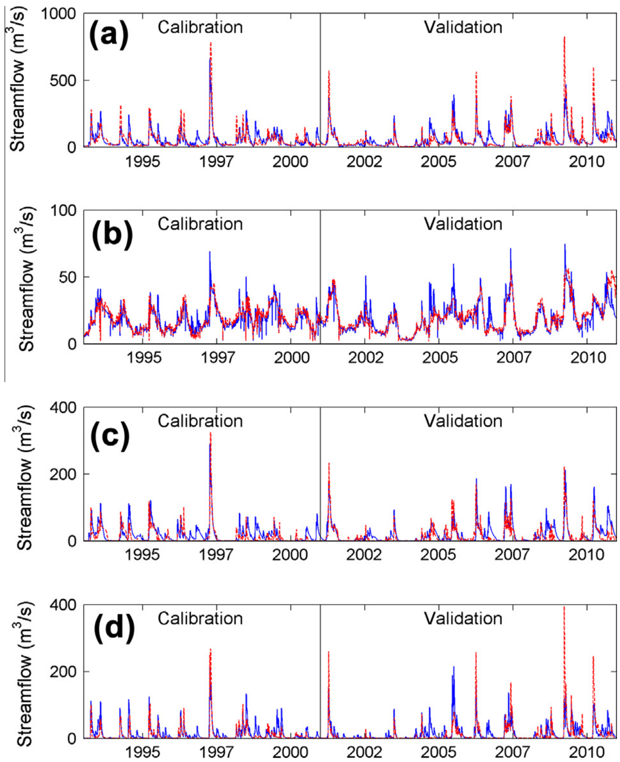

Fig. 3. Graphical comparisons of simulated (blue solid lines) and observed (red dashed lines) daily streamflows in (a) the Red River at Fargo, ND; (b) the Otter Tail River below Orwell Dam near Fergus Falls, MN; (c) the Bois de Sioux River near Doran, MN; and (d) the Wild Rice River near Abercrombie, ND. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

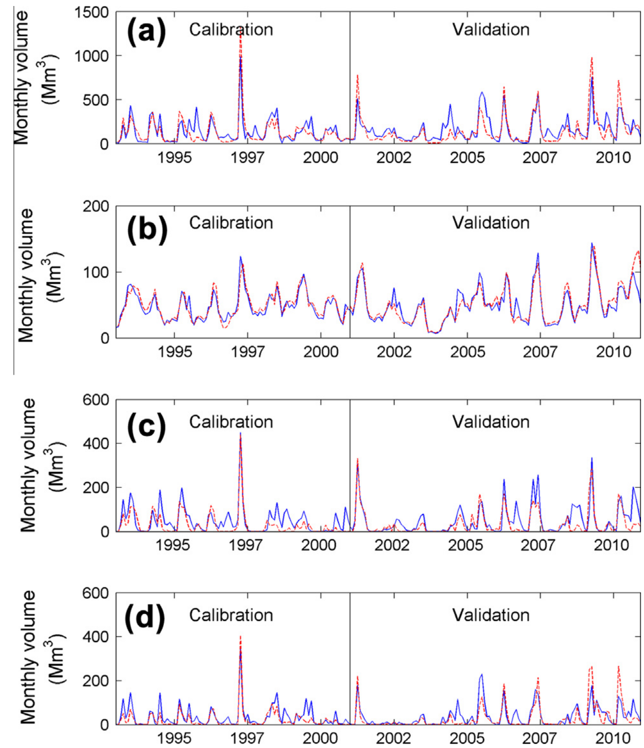

Fig. 4. Graphical comparisons of the simulated (blue solid lines) and observed (red dashed lines) monthly flow volumes in (a) the Red River at Fargo, ND; (b) the Otter Tail River below Orwell Dam near Fergus Falls, MN; (c) the Bois de Sioux River near Doran, MN; and (d) the Wild Rice River near Abercrombie, ND. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

under-predicted the peak flows (except for the Otter Tail River) as a result of spring snowmelt (see Fig. 3). A couple of reasons may be the cause of this limitation (see also Wang and Melesse, 2005; Schneider et al., 2007; Wang et al., 2008). First, SWAT was not able to simulate the intermittent snowmelt process during the late winter in the Red River basin. As suggested by Wang and Melesse (2005), the daily air temperature in the region fluctuates around the freezing point, rising above 0 °C during daytime and then falling below 0 °C at night, which causes the snowmelt water to freeze before reaching streams. Such a limitation will lead to over-predicting the snowmelt process during the late winter and leaving less snowpack for early spring melting, which eventually leads to the under-prediction of spring floods. Second, SWAT assumes that a soil column is defined as "frozen soils" when the temperature in the first layer is below the freezing point (Yang, 2011; personal communication). This assumption is valid only when the frozen depth is shallow. However, the frost depth in the RRV can reach more than 1 m. During spring snowmelt, soil temperature decreases with depth in the soil profile. Even though the first layer is thawed, the deeper soil may still be frozen, which impedes infiltration process to increase surface runoff generation. Third, during the model calibration process, we found that, when the snowmelt temperature factor (i.e., SMTMP) was increased from 0 to 1.5 °C to intensify the snowmelt process in a relatively short time period, the sublimation from snowpack would increase by about 7%, which leaves substantially less water for snowmelt runoff generation.

3.2. Streamflow impact analysis

3.2.1. Flood-frequency analysis

The annual peak flow-frequency analysis was conducted to compare the changes in flood flows in the Red River at Fargo due to expanded subsurface drainage in the URRNB. Fig. 5 compares the flood frequency curves developed under the existing and the expanded subsurface drainage scenarios. The flood frequency analysis shows that the subsurface drainage under "Expanded scenario" will increase the frequency of smaller peak flows while decreasing the frequency of greater peak flows at Fargo. In other words, the magnitudes of peak flow at greater probability of recurrence will be increased while those at the smaller probability of recurrence will be the decreased and the turning point is the peak flows with a 3.44 year return period. This return period is equivalent to the minor flood stage at the Fargo station. Fig. 5 also shows that such changes in the magnitude and frequency of peak flows are not statistically significant, given that both of the peak flow-frequency curves lie wholly within both curves' 95% confidence intervals. The 95% confidence intervals for the frequency curves are provided by the freeware MATLAB® function – b17, which are calculated based on sampling uncertainty (Burkey, 2009) rather than parametric uncertainty (Viessman and Lewis, 2003, pp. 66–67).

3.2.2. Normalized-hydrograph analysis

The ten individual normalized hydrographs based on the SWAT-simulated streamflows in the Red River at Fargo, ND are plotted in Fig. 6(a) to show the variation in hydrographs. Fig. 6(b) compares the averaged normalized hydrographs under different scenarios. A change in streamflow response may be indicated by the shape of hydrograph – a steeper rising hydrograph is normally caused by a faster speed at which the excess water moves off the basin into the main stem, resulting in a shorter duration hydrograph with a greater peak discharge if the flow volume is the same.

Fig. 6(b) shows that the normalized hydrographs of the expanded tiling scenario has a steeper rising limb. This is, if 17% of

Table 5
Statistics of the SWAT model's performance for simulating streamflows recorded at four USGS gage stations in the upper Red River of the North basin.

USGS stations	Calibration (1993–2000)		Validation (2001–2010)	
	NSE	PBIAS (%)	NSE	PBIAS (%)
Daily streamflows				
Red River at Fargo, ND	0.65	14.5	0.68	10.8
Otter Tail River below Orwell Dam near Fergus Falls, MN	0.73	−2.8	0.76	−3.6
Bois de Sioux River near Doran, MN	0.33	62.3	0.37	44.7
Wild Rice River near Abercrombie, ND	0.50	55.5	0.51	22.3
Monthly volumes				
Red River at Fargo, ND	0.72	7.6	0.66	15.6
Otter Tail River below Orwell Dam near Fergus Falls, MN	0.86	−2.8	0.82	−3.5
Bois de Sioux River near Doran, MN	0.49	62.3	0.46	44.7
Wild Rice River near Abercrombie, ND	0.64	55.6	0.57	22.2

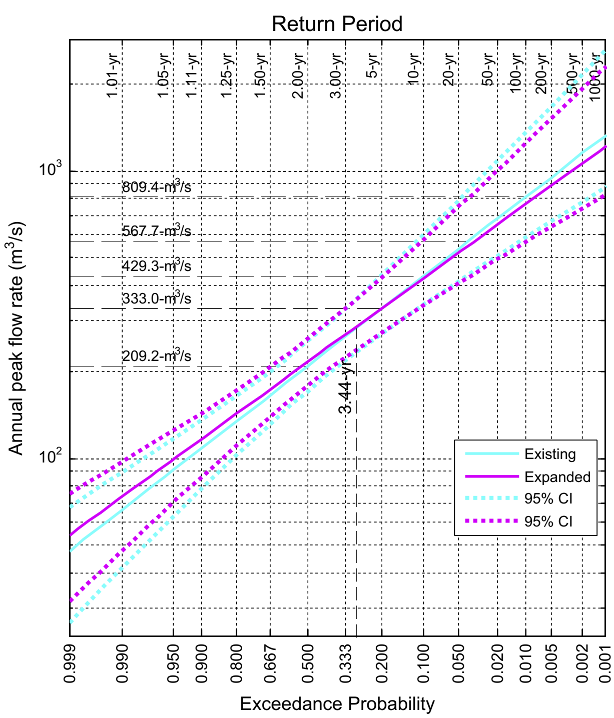

Fig. 5. Annual peak flow-frequency analysis for the Red River of the North at Fargo, ND.

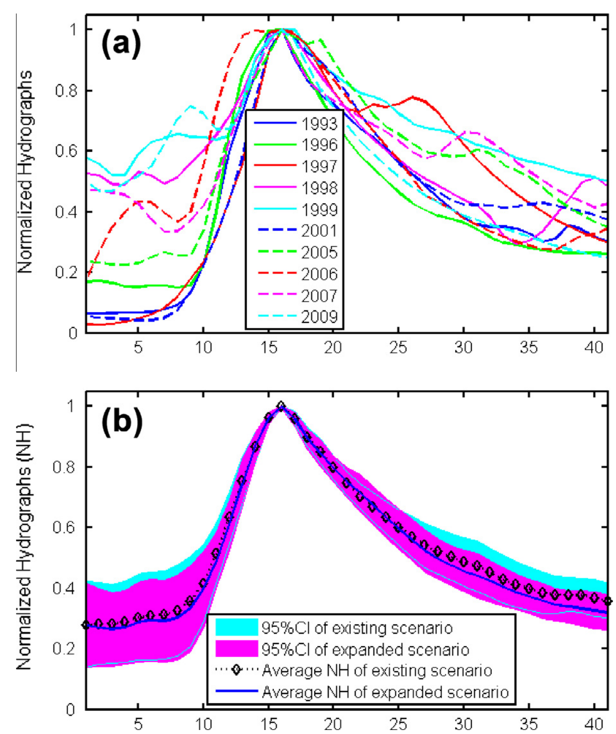

Fig. 6. Normalized-hydrograph (NH) analysis based on the SWAT-simulated streamflows in the Red River of the North at Fargo, ND: (a) individual normalized hydrographs, and (b) average normalized hydrographs and confidence intervals.

the URRNB were under tile drainage (about 40% of the Red River Valley), the time-to-peak of the hydrographs in the Red River at Fargo would be slightly shorter than that under the existing tiling condition. Thus, if the flow volume remained the same, then the peak discharges would become greater under the expanded tiling scenario. Combined with the results of the previous flood-frequency analysis, this implies that the reduction of the peak flow rates at smaller recurrence probabilities under the expanded tiling scenario is mainly caused by reducing the flow volumes rather than through increasing the time-to-peak of hydrograph. As in flood frequency analysis, Fig. 6(b) also shows that such alteration in the shape of hydrograph is not statistically significant, given that both of the normalized hydrographs lie wholly within both hydrographs' 95% confidence intervals.

3.2.3. Seasonal streamflow analysis

Fig. 7(a and b) shows the average monthly flow volumes under both the existing and expanded tiling scenarios. Fig. 7(a) compares the mean monthly flow volumes averaged over all simulation years (from 1993 to 2010); while Fig. 7(b) compares the mean monthly flow volumes averaged over the seven wettest years during the simulation period (including 1997, 1998, 2001, 2005, 2006, 2009, and 2010).

The expanded tiling scenario in Fig. 7 demonstrates that the average monthly flow volumes will decrease during the winter months (December–February) and increase during late summer and fall (August–November). In the spring and early summer, the results are mixed. For all years, the extensive subsurface drainage will increase the average monthly flows from March to July except for May; for the wettest years, subsurface drainage will decrease the average monthly flows from April to July but increase in March. The simulation results indeed corroborated with the conjecture that extensive subsurface drainage in the RRV would allow more water to be moved from the watershed to the rivers in the fall season, creating more storage capacity in the soils. However, such increase in storage capacity in soils has negligible effect in reducing the monthly volumes in the spring months in the following year.

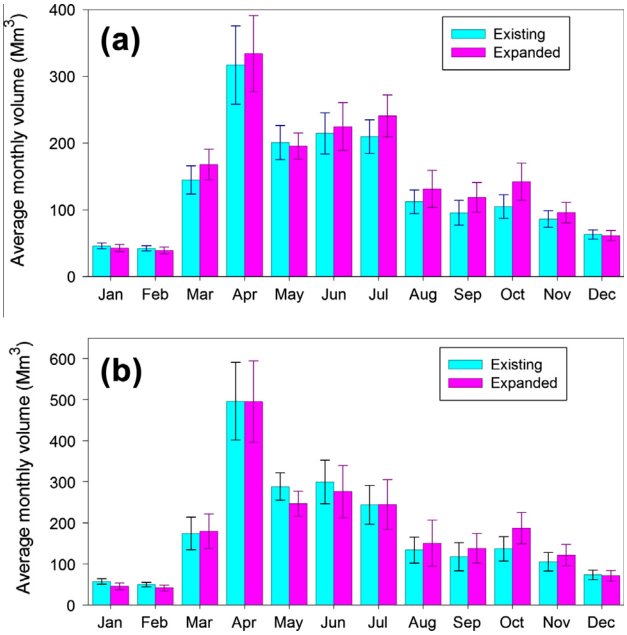

Fig. 7. Average monthly flow volume comparisons under the existing and the expanded tiling scenarios (a) for all years (1993–2010), and (b) for wet years (1997, 1998, 2001, 2005, 2006, 2009, 2010). Note: the vertical lines represent the standard errors.

4. Conclusions

Our study evaluated the applicability of the SWAT model (SWAT2009) in modeling subsurface drainage in a cold environment – the Red River of the North basin. To the best of our knowledge, this is the first time that the tile drainage algorithm adopted by SWAT is rigorously tested against the daily tile flow observations (see Ahmad et al., 2002). When calibrated against three years of daily tile flows observed at a 100% tile-drained field in the Red River of the North basin, SWAT was able to simulate the pattern of the observed tile flow with a value of 0.5 for *NSE* and −1.4% for *PBIAS*. The simulated tile flow accounted for about 16% of the annual precipitation or about 37% of the water yield, which is in a general agreement with the findings from field studies conducted in the Midwest of United States (Jin and Sands, 2003; Kladivko et al, 2004; Sands et al., 2008).

Another contribution from our research is the combined uses of SWAT modeling and streamflow response analysis for understanding the impacts of subsurface drainage on streamflows from a basin where snowmelt hydrology is important in terms of streamflow generation in the spring. First, when compared against the streamflow observations at the four USGS gage stations in the upper Red River of the North basin, the calibrated SWAT model was able to simulate the daily and monthly streamflows with reasonable success. The values of *NSE* ranged from 0.33 to 0.86 and *PBIAS* ranged from −3.6% to 62.3% for model calibration and validation. It should be noted that, since SWAT does not take into account of soil freeze–thaw processes and takes simplistic approaches to modeling soil temperature and the snow melting process, the SWAT model for the URRNB generally under-predicted the peak flows from spring snowmelt.

Second, our analysis showed that extensive subsurface drainage in the RRV would likely increase the magnitude of smaller peak flows while decreasing the magnitude of larger peak flows. Discharge reduction of large peak flows was mainly caused by reducing the flow volumes rather than increasing the time-to-peak of the hydrograph. The analysis also suggested that extensive subsurface drainage could move more water from the watershed to the rivers in the fall season, creating more storage capacity in the soils. However, such increase in storage capacity in soils would have a negligible effect in reducing the monthly flow volumes in the following spring.

Acknowledgements

This research is partially supported by North Dakota Water Resources Research Institute Graduate Fellowship program and by USDA National Institute of Food and Agriculture Projects ND01470 and ND05049. The authors wish to thank Drs Tom Scherer and Wanhong Yang for their insight and help in monitoring and modeling subsurface drainage.

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