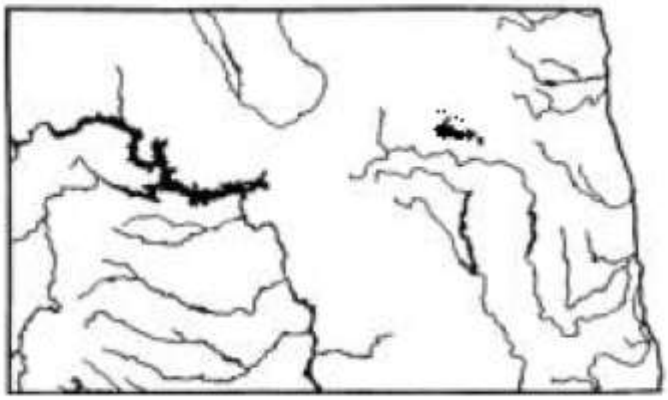

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Table of Contents

Executive Summary

Agricultural drainage and late spring snowmelt flooding are two intertwined problems in the Red River of the North in North America (i.e., the Red River). Fueled by the decades-long abnormally wet weather pattern, the two problems were exacerbated in recent years – farmers are installing subsurface drainages at an unprecedented pace and the north-flowing Red River has been experiencing ever increasing magnitudes and frequencies of spring flooding. The debate about the effects of subsurface drainage on streamflows in the Red River has attracted great attention among researchers, policymakers and practitioners.

Our study first evaluated the applicability of the Soil and Water Assessment Tool (SWAT) in modeling subsurface drainage in a cold environment, and then employed streamflow response analyses (i.e., flood frequency analysis, normalized hydrograph, and seasonal analysis) to assess the potential impacts of the extensive subsurface drainage development in the Red River Valley (RRV) on streamflows in the Red River. A watershed-scale SWAT model was developed for the upper Red River of the North Basin (URRNB). Within the watershed model, a hydrologic response unit was set up for the 20-ha subsurface drainage experiment field located at Fairmount in Richland County, ND. The parameters associated with subsurface drainage systems were calibrated using tile flow daily observations in 2008-2010 at the Fairmount tiled field, while the watershed-scale SWAT model was calibrated against daily streamflows and monthly flow volumes observed at the four USGS stream gage stations in the URRNB. When calibrated, SWAT was able to simulate the daily tile flows observed in a field study and the daily and monthly streamflows observed at four USGS gage stations with a relative success. The values of

Nash-Sutcliffe Efficiency ranged from 0.39 to 0.86 and the range of Percent of Bias was from –4.9% to 41.9%.

Three subsurface drainage scenarios were developed in the study: the baseline scenario assumes 0.7% of the URRNB (or 1.6% of the valley area) were tiled; the D soil scenario assumes 5.6% of the URRNB (or 13% of the valley area) were tiled; and the C+D scenario assumes 16.8% of the URRNB (or 40% of the valley area) were tiled. We compared the characteristics of streamflows in the Red River at Fargo under the three different tiling scenarios. Our analysis showed that there was no significant difference in streamflow characteristics under the baseline and D soil scenarios. However, the extensive subsurface drainage under the C+D scenario would likely increase the magnitudes of smaller peak flows while decreasing the magnitudes of larger peak flows; the reduction of the discharges for 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 was able to move more water from the watershed to the rivers in the fall season, creating more storage capacity in the soils. However, this increase in storage capacity in soils had negligible effect in reducing the *monthly flow volumes* in the next spring.

Acknowledgement

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1. Introduction

Agricultural drainage and late spring snowmelt flooding are two intertwined critical problems in the Red River of the North (referred to as Red River hereafter) basin (see the insert of Fig. 1) 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). Historically, there was a significant amount of drainage development in the early 1900's, shortly after the initial European settlement in the Red River Valley (RRV), and then again in the 1940's and 1950's, after World War II (Miller and Frink, 1984). The latter was believed to aggravate the flooding problem in the southern RRV (Brun et al., 1981). However, a more rigorous study conducted later by U.S. Geological Survey (Miller and Frink, 1984) was not able to conclude that the extensive artificial surface drainage in the RRV during the mid-1900's had solely increased the magnitude and frequency of large floods that had occurred during the 1940's to 1970's in the Red River basin. The regional approaches of flood-response analysis, including flood-frequency, normalized-hydrograph, double-mass, and regression analysis, suggested that the variations of the streamflows at locations on the main stem of the Red River were not significantly different from those observed in other river basins in the same region, which have been undergoing much less agricultural drainage developments than the Red River basin (Miller and Frink, 1984).

In recent years, driven by both a decades-long abnormally wet weather pattern and high agricultural commodity prices, the farmers in the RRV are installing subsurface drainage systems in their farmlands at an unprecedented pace (Pates, 2011). Since the early 1990's, the region has received an equivalent of 2-3 years additional precipitation (Jin et al., 2008), which had caused the existing surface drainage network, mainly consisting of open drains and ditches, not sufficient to maintain good internal soil drainages in farmlands. It is estimated that approximately 25% of the total crop land in the region was not planted or harvested in 1999 alone (Jin et al., 2008), resulting in great financial losses for farmers, especially with high agricultural commodity prices. In 2011, the State of North Dakota passed Senate Bill 2280 to expedite the process of obtaining a subsurface drainage permit for farmers (http://legiscan.com/gaits/view/236397; accessed August 26, 2013). At the same time, high precipitation in the past decades also increased the magnitude and frequency of Red River flooding. In 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-yr moving average of natural maximum flows increased from about 95 m^3/s (3400 ft^3/s) in 1950 to currently 225 m^3/s (8000 ft^3/s) (Foley, 2010). Because of the general belief that the purpose of subsurface drainage is to drain more water off field than under natural condition, there has been public concern that extensive subsurface drainages in the Red River basin will exacerbate the already grave flood situation in the region. However, to the agricultural community, it is self-evident that subsurface drainage lowers water table, creates storage capacity in soils to absorb excess moistures during snowmelt or heavy rainfalls, and thereby reduces downstream peak flow rates (Robinson and Rycroft, 1999). Therefore, the purpose of this study is to analyze the potential effects (i.e., magnitude and direction) of the expanded subsurface drainage in the Red River basin on streamflows.

The debate about the effects of drainage on streamflows and associated environmental impacts among researchers and practitioners has a 100 +-year tradition. Skaggs et al. (1994), Robinson and Rycroft (1999), and Blann et al. (2009) provided excellent reviews on the subject, each from a different perspective. Skaggs et al. (1994) emphasizes that we should make a distinction between an initial artificial drainage improvement accompanied with land use conversion from improved drainage when assessing the hydrologic and water quality impact of agricultural drainage. While the former almost always causes a negative impact, it is difficult to separate the effect of drainage from those caused by land use conversion. For the latter, the general consensus is that the improved *surface* drainage would increase runoff rates and have greater losses of sediment and sediment-bound pollutants while the improved *subsurface* drainage would reduce runoff and lower peak flow rates than surface drainage only. Robinson and Rycroft (1999) mainly focus on the magnitude and direction of effect on streamflows, drawing conclusions from theoretical considerations, experimental studies and computer simulations at both field and watershed scales. Blann et al. (2009) extended the review to the direct and indirect effects of drainage on aquatic ecosystems. Direct effects include habitat loss due to conversion of wetlands to croplands and stream channelization. Indirect effects include the changes in stream morphology, in-stream and riparian habitats, nutrients cycles, and biota, which are in turn caused by agricultural drainage-associated hydrologic alterations.

For the impact of subsurface drainage on streamflows, the magnitude and direction of the effect 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; 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 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 accelerate the peak subsurface flow rate.

The above findings about subsurface drainage hydrologic impact are mostly drawn from the *field-scale* experiment and modeling studies conducted in humid regions of North America and Europe, whereas relatively less research has originated from cold regions like the Red River basin (Robinson and Rycroft, 1999; Tan et al., 2002; Jin and Sands, 2003; Jin et al., 2008). At the field scale, soil types have a major impact on drainage runoffs, while at the watershed scale, the magnitude, and even direction, of the influence on streamflows due to drainage tends to be affected by other factors, such as precipitation, drainage networks, channel routing, and the distribution of the drainage works within the watershed (Robinson and Rycroft, 1999; Blann et al., 2009). It is not surprising that the magnitude of the impact of drainage will be less at the watershed scale than at the field scale because the percentage of the drained areas at the watershed scale is normally much smaller than that in a tile-drained field (Konyha et al., 1992).

Since it is almost impossible to conduct field studies to compare the drainage treatments on streamflows at large scales, 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 drainages at the watershed scale. First is to integrate subsurface drainage algorithms into watershed-scale hydrological and water quality models such as SWAT(i.e., Soil and Water Assessment Tool; 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 are 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). The other approach is to expand the applicability of the field-scale subsurface drainage model DRAINMOD to the 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 represent spatial variation in drain spacing across the entire watershed. It can be prohibitive to obtain such detail information for a large watershed.

The objective of our study is to combine the usages of watershed modeling and streamflow response analyses to assess the impact of subsurface drainage on streamflows in the Red River basin. Our specific objectives include: (1) to evaluate the applicability of SWAT in modeling the hydrology of the tile-drained watershed in a cold environment; and (2) to assess the implications of the expanded subsurface drainage on the streamflows in the Red River basin under different tiling scenarios.

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-kilometers (6500 square miles) drainage area upstream to the US Geological Survey (USGS) stream gage station (#05054000) in the Red River located at Fargo, North Dakota (Fig. 1). Like the greater Red River basin, the URRNB contains two distinct types of land forms – the level plain and the rolling upland (Referring to Fig. 1). In the center, lies are remarkably flat, northward-sloping level plain, termed the Red River Valley, which 9,000 years ago was the bottom of ancient glacial Lake Agassiz. The lake deposits, consisting of sorted and stratified clay and silt, are as much as 95 ft thick in the valley. Extending east and west of the central plain are gently rolling uplands dotted with prairie potholes and depressions. The glacial drift in the uplands consists of an unsorted and un-stratified mixture of clay, silt, sand, and gravel, commonly referred to as till (Miller and Frink, 1984; Stoner et al., 1993).

The major land uses 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 colder winters and moderately warm summers. Mean annual precipitation in the basin is about 500 mm and about three-fourths falls from April through September. December through February are usually the driest months. The growing season runs from middle May through middle 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 resorted to in order 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 (0.2 to 1.3 feet per mile) is prone to spring flooding. Many statements have been made concerning about how agricultural drainage affects the magnitude and the timing of the peak flows in the Red River (Anderson and Kean, 2004; North Dakota Natural Resources Trust, 2011). Because of the complexity of the runoff generation and routing processes, the effect could probably be characterized only with the use of a basin-wide flow model.

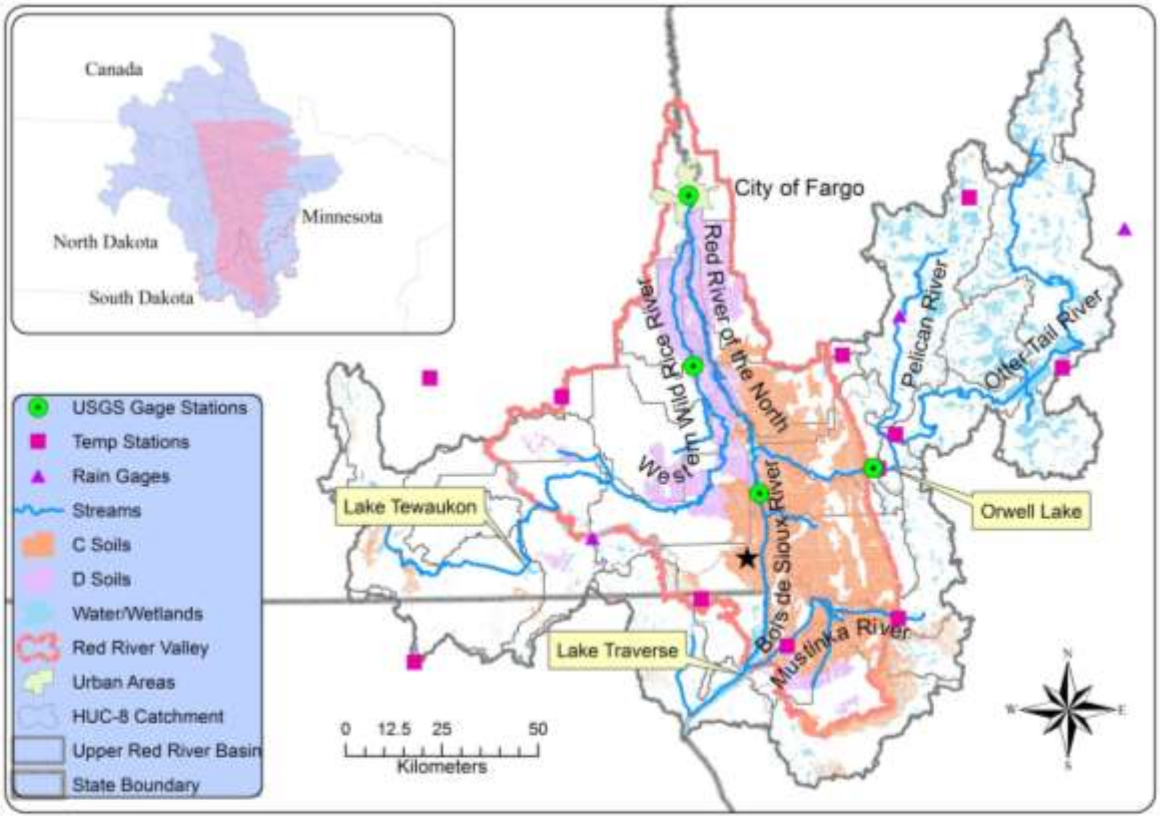

Fig. 1. The geophysical location of the upper Red River of the North basin with the star indicating the location of the Fairmount experimental site.

2.2 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 (HRU's) that are unique combinations of different land uses, soils, and surface slopes. Within each subbasin the areas with similar land use, soils types, and surface slopes are lumped together into a single HRU and the different HRU’s 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 SWAT model is arguably one of the most widely-used watershed models and it has been used to model water, sediment and nutrient movements in basins ranging from 3 to 598,538 km^2 (Spruill et al., 2000). The processes concerned 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). For this study, we are most concerned with the subsurface drainage algorithm adopted by SWAT and SWAT’s application in the cold environment.

The tile drainage algorithms in SWAT have been refined over the years to better model agricultural watershed with subsurface drainage systems installed (Arnold et al., 1999; Du et al., 2005; Green et al., 2006; Moriasi et al., 2007; 2009). First, excess water in the root zone is considered when estimating plant growth stress. When soil approaches saturation, plants may suffer from aeration stress (Du et al. 2005). 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 field capacity and the additional water to fill the profile upward from the saturated bottom layers (Du et al., 2005; see also Moriasi et al., 2009). The tile flow calculation equation has also been improved to include the difference between soil water content and the field capacity, that is, the second parenthesis in Eq. (1), which is used by the current SWAT model (Release 2009) to estimate the daily drained water flow from soil profile above the tile drains (Neitsch et al. 2009).

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

where $tile_{wtr}$ is the tile drained water (mm) from soil profile; SW is 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 soil to FC. The tile drained water estimated by Eq. (1) is then routed to the main channel by Eq. (2):

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

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 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).

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

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

The snowmelt algorithms in SWAT have also been improved over the years (Levesque et al. 2008). The current SWAT model 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). The current SWAT model and its snowmelt algorithms have been extensively tested when modeling hydrology and water quality components in the cold climate (Benaman et al., 2005; Srivastava et al., 2006; Ahl et al., 2008; Chaponniere et al., 2008; Levesque et al. 2008; Sexton et al., 2010; Flynn and Van Liew, 2011; to name just a few). More specifically, Wang and Melesse (2005) evaluated the SWAT snowmelt algorithm in a subbasin of the Red River basin. They reported satisfactory monthly and seasonal performances and acceptable daily performances in simulating streamflows predominantly generated from melting snows (see also Wang and Melesse 2005; Wang et al. 2008).

2.3 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 the 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 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 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 setup for the 20-ha subsurface drainage experiment field located at Fairmount in Richland County, ND (Fig. 1). Tile flow recordings from the 100% tile-drained field were collected for 2008-2010. Corns was grown in 2008-2009 and soybean were grown in 2010 in the field. The two major soil types are Clearwater-Reis silty clay and Antler-Mustinka silty clay loam. Detailed description about the field and the experiment is provided in Jia et al. (2012).

2.4 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 1993-2002 and the validation period is 2003-2010. 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 (~ 0.7%). 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 different potential tiling scenarios in the URRNB.

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*	Depth of impervious layer (mm)	—	1250
DDRAIN*	Depth to subsurface drain (mm)	900	1180
TDRAIN*	Time to drain soil to field capacity (hrs)	48	48
GDRAIN*	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 – 14250
WET_NSA	Surface area at normal water level (ha)	—	2000 – 7000
WET_MXSA	Surface area at maximum water level (ha)	—	2200 – 21500
WET_K	Hydraulic conductivity of bottom (mm/hr)	—	0.5 – 433.0

* Subsurface drainage parameters were calibrated at the field scale.

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 i^{th} observed and predicted streamflows, respectively; $\bar{O}$ is the average observed streamflows; and n is the number of observations. The NSE takes a value from -∞ 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).

2.5 Subsurface drainage scenarios

It is reasonable to assume that the potential locations of the tile drained fields will be in where row crops are grown on flat lands with poorly drained, heavy 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, heavy clay 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 overlay the soil, land use, and surface slope (derived from DEM) data layers. If a spatial unit has a value of D for soil, of row crop for land use and less or equal to 1% for surface slope, then the spatial unit could be potentially tile-drained. For convenience, we denote this potential tiling scenario in the URRNB as “D soil scenario”. The areas of the potentially tile-drained fields and their distribution among subbasins in the SWAT model under the “D soil scenario” are listed in Table 2. However, it is evident that, in the URRNB, a high percentage of the existing subsurface drainage systems are actually installed in the field of permeable C soil (Jia and Scherer, personal communication). Therefore, for the second tiling scenario, we included both C and D soils in the tile-drained area estimation process described above. We denote this tiling scenario as “C+D scenario”. Similarly, the areas of the potentially tile-drained fields and their distribution among subbasins in the SWAT model under “C+D scenario” are also listed in Table 2. Based on the county-level tile drainage records (Sugg, 2007; Schuh, 2008), the existing tiled area was estimated to be 125 km^2 in the URRNB, equivalent to 0.75% 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 C soils. We denote the existing tiled area scenario as “Baseline scenario”.

In terms of climate scenario in the future, we simply assume the climate condition will be exactly the same as in 1991-2010 when conducting the following streamflow impact analysis under various subsurface drainage scenarios.

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

Streams (HUC-8 catchment)	Total drainage area (km^2)	Baseline scenario		D soil scenario		C+D scenario	
		Total tiled area (km^2)	Tiling percentage (%)	Total tiled area (km^2)	Tiling percentage (%)	Total tiled area (km^2)	Tiling percentage (%)
Mustinka River	2228	34.7	1.6	71.1	3.2	594.2	26.7
Bois de Sioux River	2875	11.6	0.4	22.1	0.8	837.9	29.1
Western Wild Rice River	5788	26.5	0.5	530.8	9.2	665.6	11.5
Otter Tail River	4947	14.7	0.3	19.3	0.4	212.5	4.3
Upper Red River	1060	29.8	2.8	296.3	28.0	536.2	50.6
Total or Average	16898	117.3	0.7	939.6	5.6	2846.4	16.8

2.6 Streamflow response analysis

Three hydrologic analyses – flood-frequency analysis, normalized-hydrography analysis, and seasonal streamflow analysis – have been conducted in an attempt to identify any significant changes in streamflow response due to the potential subsurface drainage in the Red River basin. The USGS stream gage station at Fargo, North Dakota, is selected as the point of interest for analysis. The purpose of the flood-frequency analysis is to identify if there are any changes in the magnitude and the frequency of annual peak flows in the Red River at Fargo under extensive tiling scenarios in the basin. We compared the annual peak-flow frequency curves of the Red River at Fargo during a 20 year period under the baseline, D soil, and C+D scenarios. The annual peak-flow-frequency analysis was conducted using a freeware Matlab function – b17 (http://www.mathworks.com/matlabcentral/), which was developed using 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 the general agreement is that subsurface drainage decreases the speed at which the excess water moves off 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 under a tiled scenario would have steeper rising and falling limbs than that under the non-tiled scenario, or vise 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 4,000 ft^3/s);
4. Complete daily record for the 31-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 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 durations to be 31 days. All normalized-hydrographs are centered on the 16th day when the peak discharge occurs.

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 4/18
1996	3/31 to 4/30
1997	3/25 to 4/24
1998	3/22 to 4/21
1999	3/25 to 4/24
2001	3/26 to 4/25
2005	2/26 to 3/28
2006	3/22 to 4/21
2007	3/26 to 4/25
2009	3/31 to 4/30
Total number of years:	10

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 years period under three different tiling scenarios.

3. Results and discussion

3.1 Model calibration and parameter estimation

3.1.1 Subsurface drainage parameters estimation at the field scale

As shown in Eq. (1)-(3) and in Table 1, the 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 soil to field capacity (TDRAIN), and the drain tile lag time (GDRAIN). While the value of DDRAIN was fixed at the burying 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.

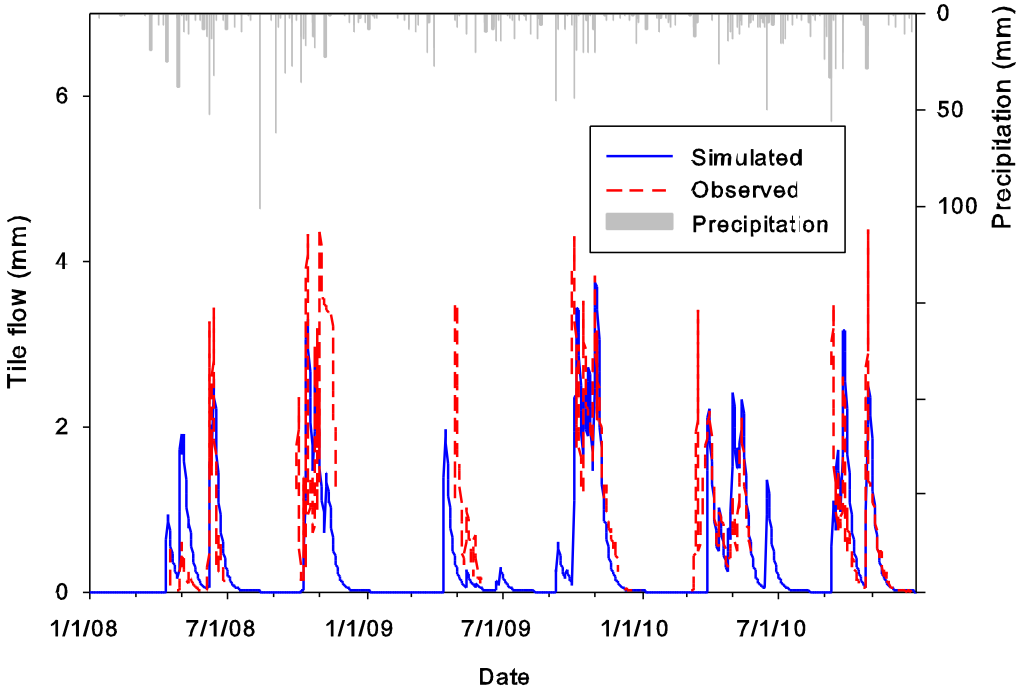

Fig. 2. Graphical comparison of simulated and observed daily tile flows at the Fairmount study field.

Fig. 2 showed that the simulated tile flow largely captured the pattern of the observed tile flow from the 100% tiled field – significant tile flows observed during spring and fall seasons while 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 also should 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 in the region were asked to shut down their sump pumps before the Red River crested.

Table 4 compared the SWAT-simulated hydrologic components (except for precipitation) in the Fairmount field during 2008-2010 with or without tile drains installed. All components are averages 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. However, when examining the hydrologic component in individual years (not shown), we found a mixed effect of tile drainage on water yield that the water yield increased about 18% in 2008; but decreased about 3% in 2009. The difference was that 2008 was a wet year with an annual precipitation of 800 mm while 2009 was relatively a drier year with an annual precipitation of 646 mm. 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 decrement 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).

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*	2	121	119
Water yield (surface runoff +subsurface flows)	299	330	31
Soil water content	247	214	–33

* 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 Fig. 3 and Fig. 4 and the statistics for model's performance are listed in Table 5. The values of the calibrated SWAT parameters are summarized in Table 1.

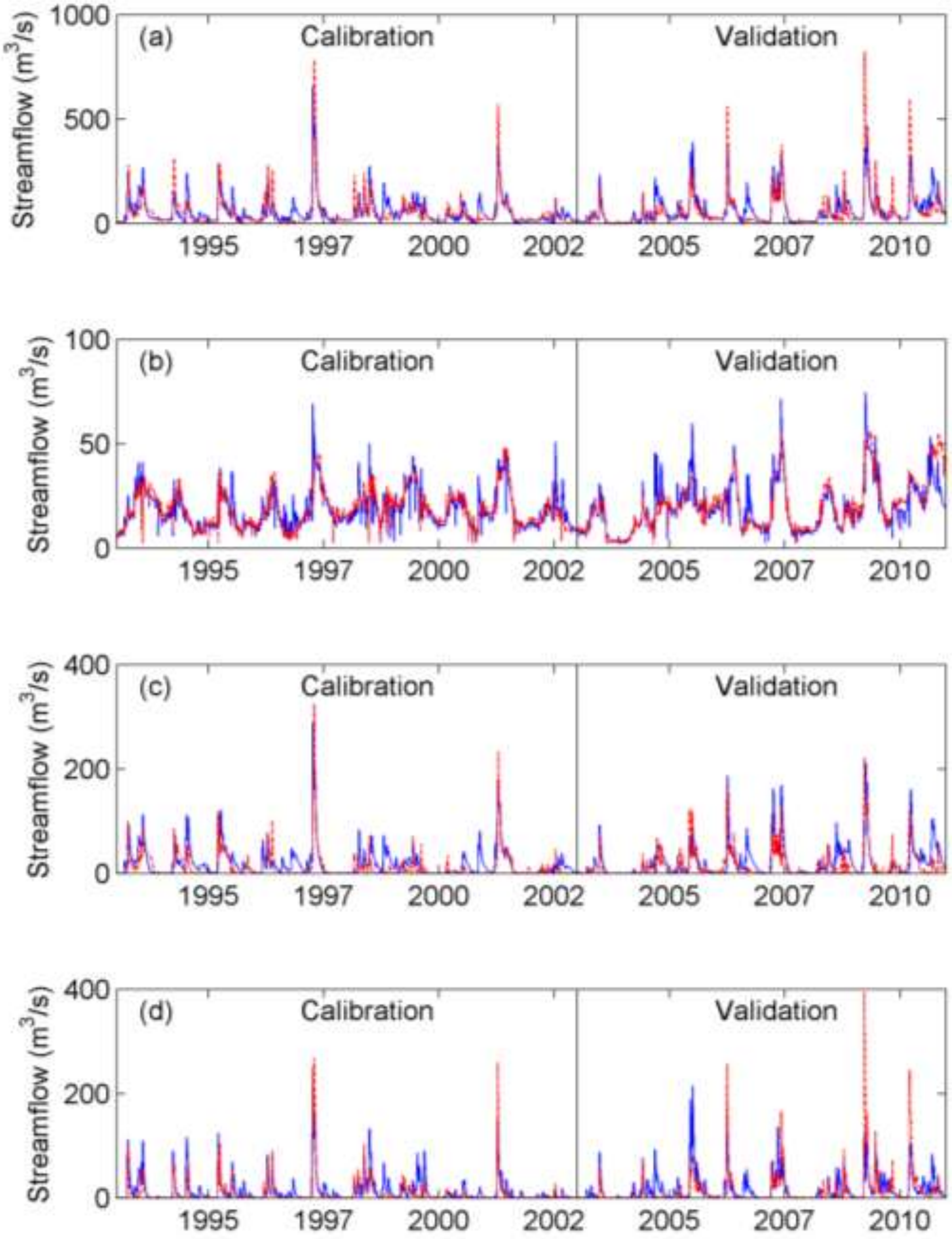

Fig. 3. Graphical comparisons of simulated (blue solid lines) and observed (red dashed lines) daily streamflows in (a) the Red River at Fargo, ND; (b) the Otter Tail River below Orwell Dam near Fergus Falls, MN; (c) the Bois de Sioux River near Doran, MN; and (4) the Wild Rice River near Abercrombie, ND.

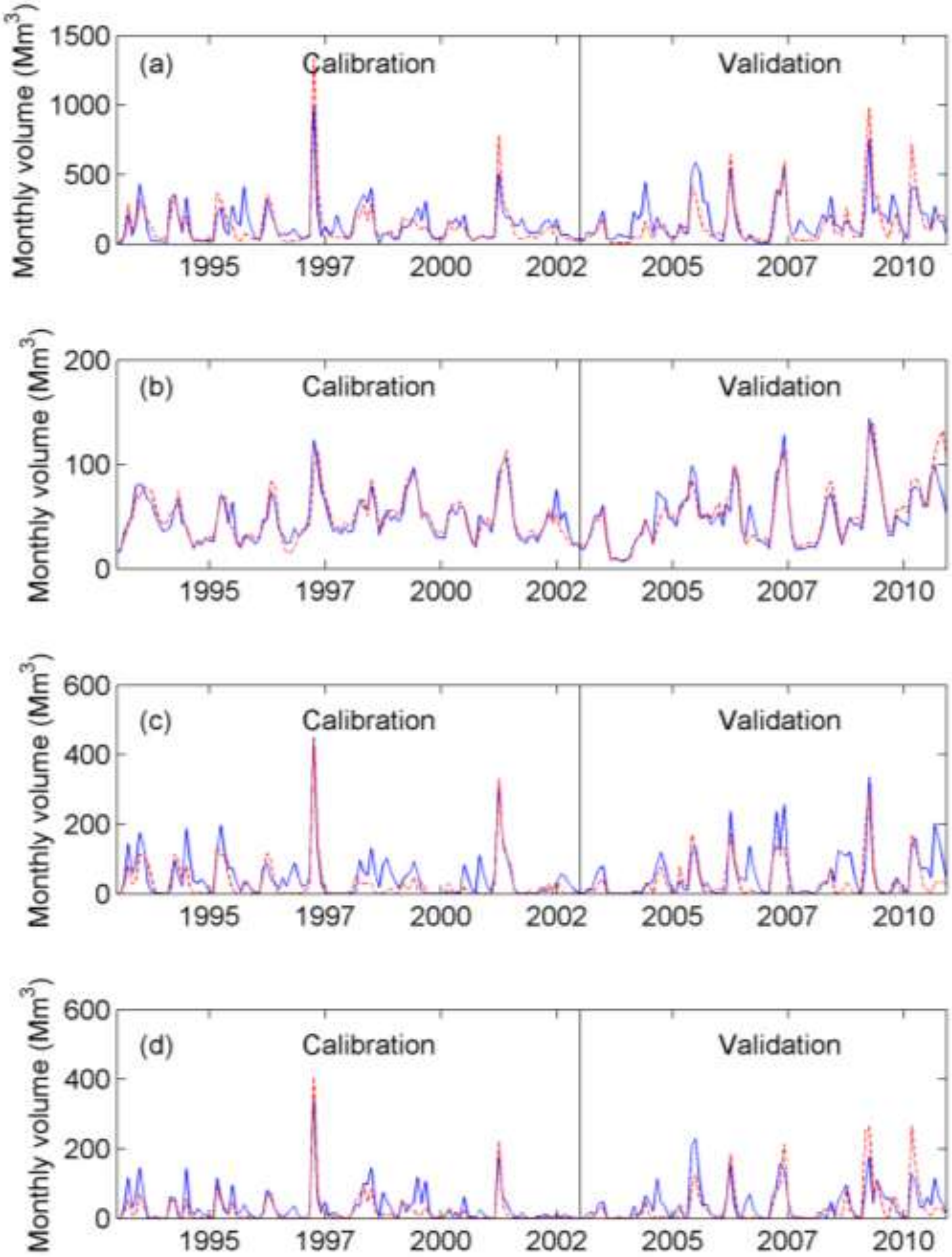

Fig. 4. Graphical comparisons of the simulated (blue solid lines) and observed (red dashed lines) monthly flow volumes in (a) the Red River at Fargo, ND; (b) the Otter Tail River below Orwell Dam near Fergus Falls, MN; (c) the Bois de Sioux River near Doran, MN; and (4) the Wild Rice River near Abercrombie, ND.

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 (1993-2002)		Validation (2003-2010)	
	NSE	PBIAS (%)	NSE	PBIAS (%)
Daily streamflows				
Red River at Fargo, ND	0.69	11.3	0.65	13.5
Otter Tail River below Orwell Dam near Fergus Falls, MN	0.75	–1.8	0.74	–4.9
Bois de Sioux River near Doran, MN	0.55	41.8	0.39	41.9
Wild Rice River near Abercrombie, ND	0.57	19.0	0.45	22.1
Monthly volumes				
Red River at Fargo, ND	0.73	8.3	0.64	16.3
Otter Tail River below Orwell Dam near Fergus Falls, MN	0.86	–1.8	0.81	–4.9
Bois de Sioux River near Doran, MN	0.62	41.8	0.44	41.9
Wild Rice River near Abercrombie, ND	0.69	18.6	0.50	22.1

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 (1993-2002) and validation period (2003-2010). 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 operations of Lake Traverse in the Bois de Sioux River and Lake Tewaukon in the Wild Rice River. In addition, the model under-predicted streamflows for the Otter Tail River while over-predicting streamflows for the other three streams (see Table 5).

Although the SWAT model did very well in modeling the peak flows in the historic spring flood in 1997, the model generally under-predicted the peak flows as a result of spring snowmelt. A couple of reasons may be attributed to 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 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 freezing point (Wanhong Yang, personal communication). This assumption is valid only when the frozen depth is shallow. However, the frozen soils in the RRV can reach more than 1 m deep. During spring snowmelt, soil temperature decreases along 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 moisture 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 three different subsurface drainage scenarios. Fig. 5 shows that the flood frequency curves for the streamflows under the baseline and the D soil scenarios overlap with each other, implying no difference in flood frequency in the Red River at Fargo under the two tiling scenario. But, the analysis also shows that the extensive subsurface drainage under the C+D scenario will likely 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 decreased. This return period of 3.44 years is equivalent to the minor flood stage at the Fargo station.

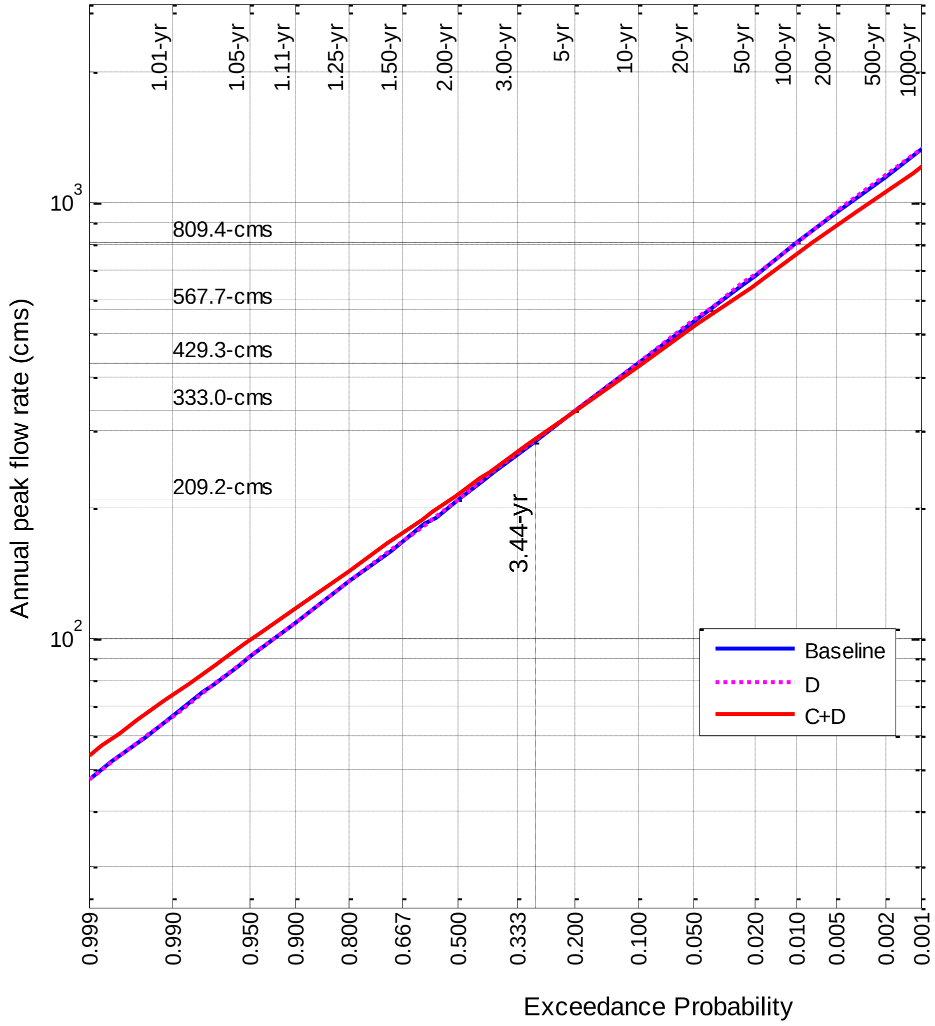

Fig. 5. Annual peak-flow-frequency analysis for the Red River of the North at Fargo, ND.

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 tiling 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 but with nearly the same volume.

Fig. 6(b) shows that the normalized hydrographs of the baseline and the D soil scenarios are almost identical, but that of the C+D scenario has a steeper rising limb. This is to say, tiling up to 5.6% of the URRNB (about 13% of the Red River Valley) will not alter the shape of the hydrograph in the Red River at Fargo. If 17% of the URRNB were under tile drainage (about 40% of the Red River Valley), the time-to-peak in the Red River at Fargo would be slightly shortened and the peak discharge would be greater than under the existing condition. However, Fig. 6(b) shows that such alteration in the shape of hydrograph is not statistically significant, given that the 95% confidence intervals of the baseline and the C+D scenarios overlap with each other.

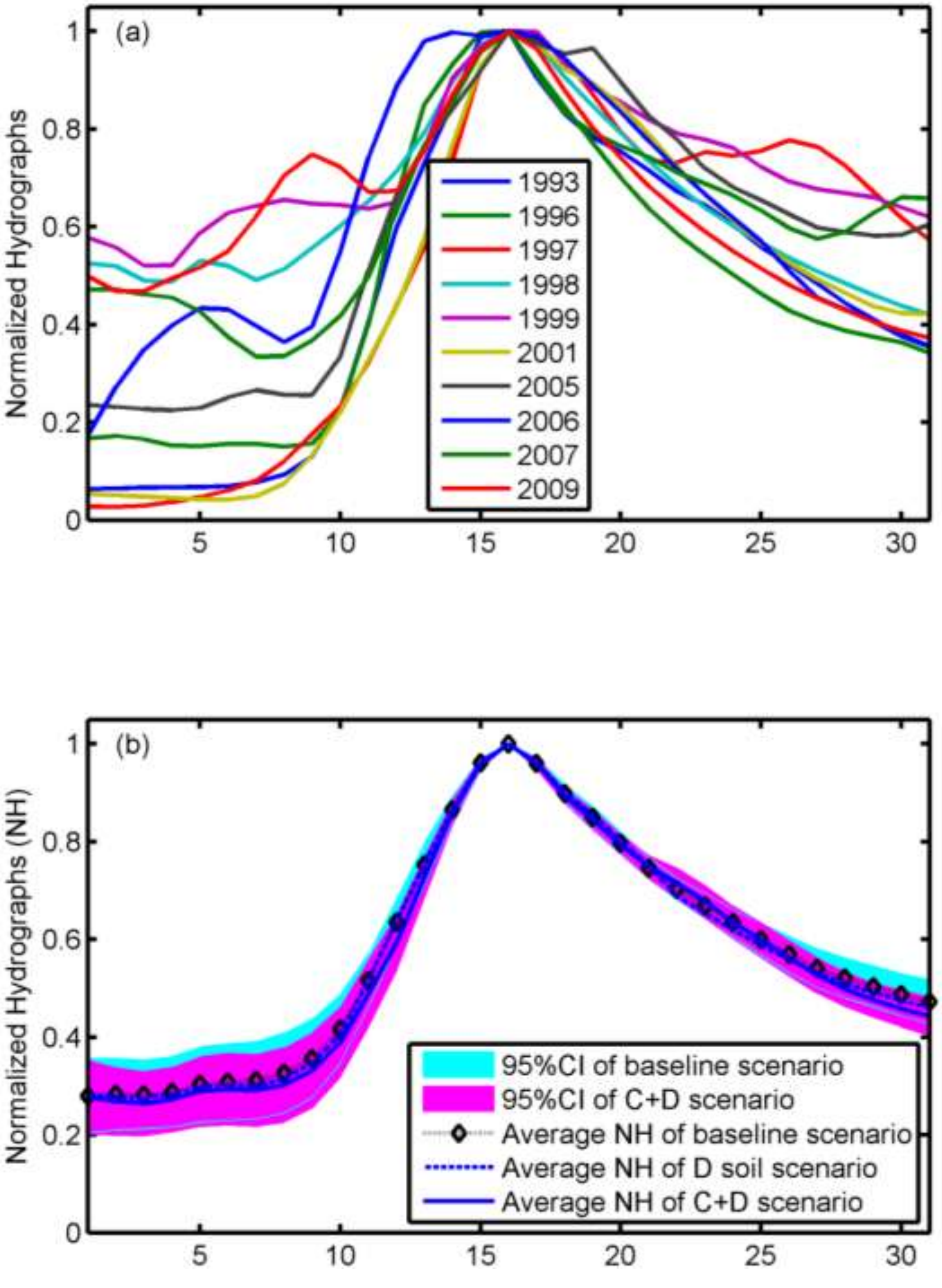

Fig. 6. Normalized-hydrograph analysis based on the SWAT-simulated streamflows in the Red River of the North at Fargo, ND: (a) individual normalized hydrographs, and (b) average normalized hydrographs and confidence intervals.

3.2.3 Seasonal streamflow analysis

Fig. 7 shows the average monthly flow volumes under both the baseline and the C+D tiling scenarios. The average monthly flow volume under the D soil tiling scenario was not shown for the clarity reason. Fig. 7(a) compares the mean monthly flow volumes averaged over all simulation years (from 1993 to 2010); while Fig. (b) compares the mean monthly flow volumes averaged over the seven wettest years among the simulation period (including 1997, 1998, 2001, 2005, 2006, 2009, and 2010).

Fig. 7 shows that, under the expanded tiling scenario, 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.

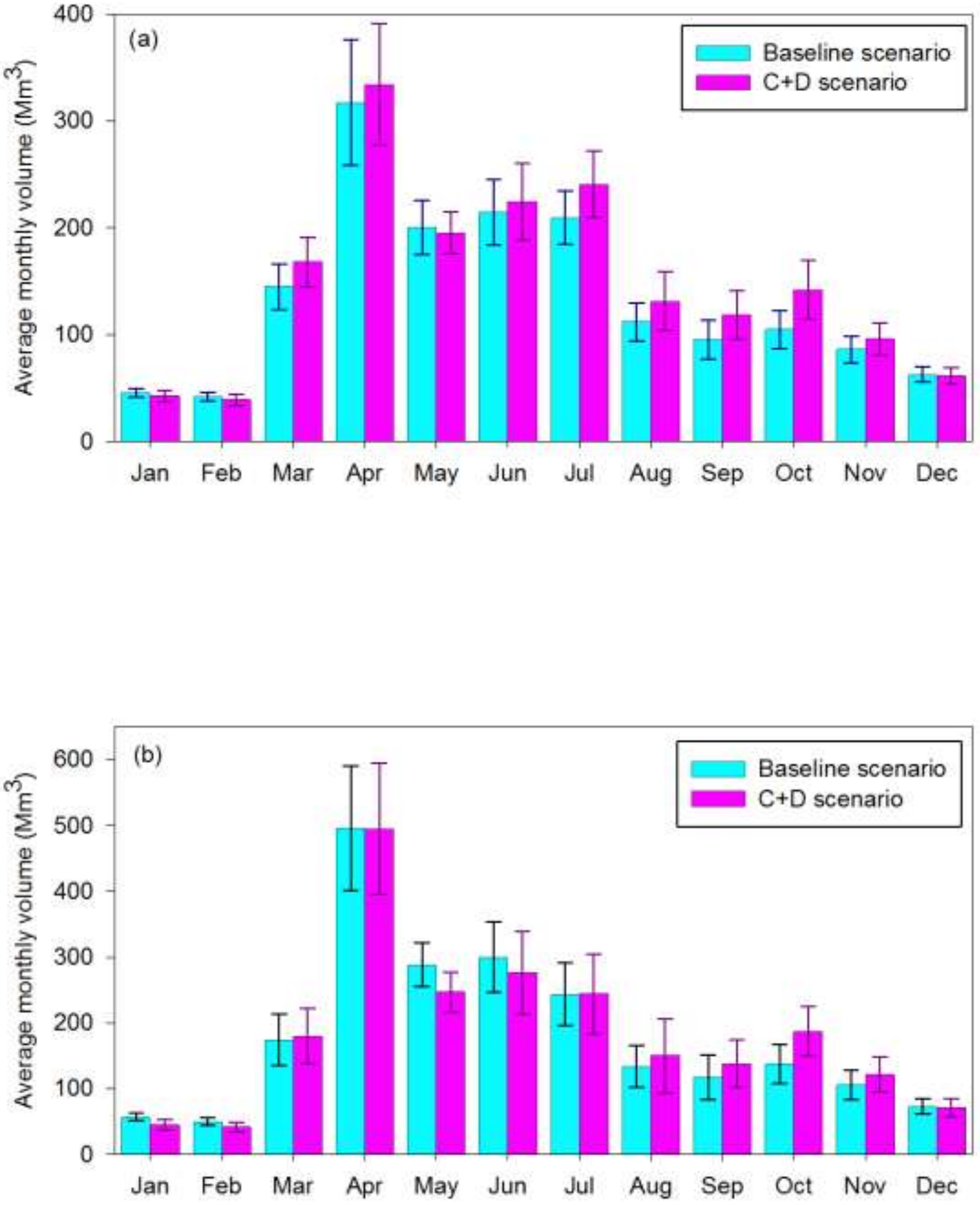

Fig. 7. Average monthly flow volume comparisons under the baseline and C+D scenarios (a) for all years (1993-2010), and (b) for wet years (1997, 1998, 2001, 2005, 2006, 2009, 2010). Note: the vertical lines represent the standard errors.

4. Conclusions

The impact of subsurface drainage on streamflows depends on climate conditions, topography, drainage channel networks, drainage designs, and many site-specific factors such as soil properties, antecedent soil water content, and tillage practices (Robinson, 1990; Skaggs et al., 1994; Wiskow and van der Ploeg, 2003; Blann et al., 2009). At the field scale, where soil types have a major impact on drainage runoffs, field studies are normally carried out to study the hydrologic impacts of subsurface drainage. At the watershed scale, where many factors affect the magnitude and direction of the influence of subsurface drainage on streamflows, hydrologic models are usually employed to study the impact. In the literature, most field and modeling studies are conducted in humid regions of North America and Europe (Robinson and Rycroft, 1999; Tan et al., 2002). In a cold climate, the impact of subsurface drainage on streamflows may be affected by the soil freeze-thaw and snowmelt processes, which in turn may be affected by the higher soil temperature in the tile-drained fields. It is believed that the dryer soil in the tile-drained field may be warmed up faster in the spring after snow cover is gone (Jin et al. 2008).

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. Calibrated against three years of tile flow data observed at a 100% tile-drained field in the RRV, 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 in the Midwest of United States (Jin and Sands, 2003; Kladivko et al, 2004; Sands et al., 2008). SWAT also did well in simulating the daily and monthly streamflows observed at the four USGS gage stations in the upper Red River of the North Basin, with the values of NSE ranging from 0.39 to 0.86 and PBIAS from -4.9% to 41.9% during the model calibration (1993-2000) and validation (2001-2010) periods. Since SWAT does not take into account the soil freeze-thaw processes and takes simplistic approaches to modeling soil temperature and snow melting process, the SWAT model for the URRNB generally under-predicted the peak flows from spring snowmelt.

In conjunction with SWAT modeling, three streamflow response analysis methods, namely flood frequency analysis, normalized hydrograph, and seasonal analysis, were employed to assess the potential impacts of the extensive subsurface drainage development in the RRV on streamflow in the Red River. We compared the characteristics of peak flow frequency, hydrographs, and average monthly volumes in the Red River at Fargo under the existing and expanded tiling scenarios. Our analysis showed that extensive subsurface drainage (up to 17% of the basin area or equivalent to 40% of the valley area) will increase the magnitudes of smaller peak flows while decreasing the magnitudes of larger peak flows. Our analysis also showed that the reduction of the discharges for large peak flows (i.e., peak flows at smaller recurrence probabilities) under the extensive subsurface drainage is mainly caused by reducing the flow volumes rather than through increasing the time-to-peak.

The seasonal analysis showed that extensive subsurface drainage in the RRV will increase the average monthly flows in the Red River during late summer and fall (August-November), suggesting that extensive subsurface drainage is able to move more water from the watershed to the rivers in the fall season, creating more storage capacity in the soils. However, our simulation results also indicated that such increase in storage capacity in soils had negligible effect in reducing the monthly flow volumes in the next spring.

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