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

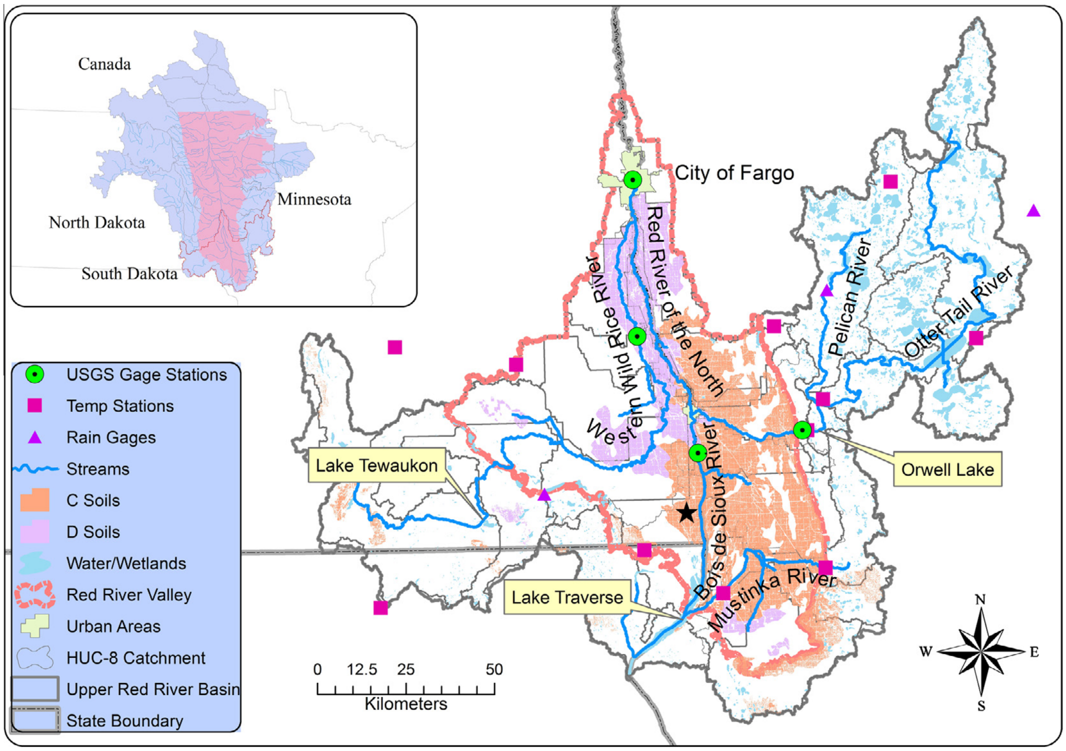

Fig. 1. The geophysical location of the upper Red River of the North basin with the star indicating the location of the Fairmount experimental site.

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.