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Simulated wetland conservation-restoration effects on water quantity and quality at watershed scale

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ABSTRACT

Wetlands are one of the most important watershed microtopographic features that affect hydrologic processes (e.g., routing) and the fate and transport of constituents (e.g., sediment and nutrients). Efforts to conserve existing wetlands and/or to restore lost wetlands require that watershed-level effects of wetlands on water quantity and water quality be quantified. Because monitoring approaches are usually cost or logistics prohibitive at watershed scale, distributed watershed models such as the Soil and Water Assessment Tool (SWAT), enhanced by the hydrologic equivalent wetland (HEW) concept developed by Wang [Wang, X., Yang, W., Melesse, A.M., 2008. Using hydrologic equivalent wetland concept within SWAT to estimate streamflow in watersheds with numerous wetlands. Trans. ASABE 51 (1), 55–72.], can be a best resort. However, there is a serious lack of information about simulated effects using this kind of integrated modeling approach. The objective of this study was to use the HEW concept in SWAT to assess effects of wetland restoration within the Broughton's Creek watershed located in southwestern Manitoba, and of wetland conservation within the upper portion of the Otter Tail River watershed located in northwestern Minnesota. The results indicated that the HEW concept allows the nonlinear functional relations between watershed processes and wetland characteristics (e.g., size and morphology) to be accurately represented in the models. The loss of the first 10–20% of the wetlands in the Minnesota study area would drastically increase the peak discharge and loadings of sediment, total phosphorus (TP), and total nitrogen (TN). On the other hand, the justifiable reductions of the peak discharge and loadings of sediment, TP, and TN in the Manitoba study area may require that 50–80% of the lost wetlands be restored. Further, the comparison between the predicted restoration and conservation effects revealed that wetland conservation seems to deserve a higher priority while both wetland conservation and restoration may be equally important.

1. Introduction

Wetlands share properties of both terrestrial and aquatic systems, and of both lotic and lentic systems (Cowardin et al., 1979; Howard-Williams, 1985). For a watershed, wetlands serve important hydrologic, geochemical, and biological functions (De Laney, 1995; Hart, 1995; NRC, 1995). Thus, the conservation of existing wetlands (USDA-NRCS, 2007) and the restoration of lost/degraded wetlands (Dahl and Johnson, 1991; Gleason and Euliss, 1998) have been considered as an important means for mitigating flood runoff (Leavesley and Stannard, 1995; Padmanabhan and Bengtson, 2001; Leavesley et al., 2002) and abating sediment and nutrients (e.g., phosphorus and nitrogen; Yates and Sheridan, 1983; Crumpton and Goldsborough, 1998; Kadlec, 2008; Yang et al., 2008). Although the effects can be monitored for existing wetlands either individually or together at a small (i.e., demonstration-level) scale (e.g., Quinton et al., 2003; Hayashi et al., 2004; Kadlec, 2008), the monitoring approach can be cost as well as logistics prohibitive at watershed scale (Finlayson, 2003) and becomes infeasible for proposed wetlands.

However, practices usually require a wetland conservation/restoration scenario be quantitatively assessed to show measurable effects in improving the overall watershed health, i.e., in reducing loadings of sediment and nutrients to be transported out of a watershed of interest (Arheimer and Wittgren, 2002; Trepel and Palmeri, 2002). In contrast with the monitoring approach, watershed modeling using distributed hydrologic models, such as the

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Soil and Water Assessment Tool (SWAT; Arnold et al., 1998; Arnold and Fohrer, 2005), has proven to be very efficant in predicting impacts of management practices on water, sediment, and agricultural chemical yields in large ungauged watersheds (Gassman et al., 2007). Coupled with the "hydrologic equivalent wetland" (HEW) concept developed by Wang et al. (2008), SWAT can be used to reliably predict effects of wetland conservation/restoration scenarios and to logically prioritize restoration efforts (Yang et al., 2008). An application tendency is to integrate monitoring approach with watershed modeling. For example, the U.S. Environmental Protection Agency (EPA) developed and implements a "three-tier" approach (Kentula, 2007). This approach consists of landscape or level 1 assessment methods, rapid or level 2 assessment methods, and intensive or level 3 assessment methods. The methods for levels 1 and 2 are based on mathematic models that have variables of field condition scores as well as hydrology and/or watershed practice indicators (Fennessy et al., 2007; Whigham et al., 2007), whereas, the methods for level 3 are based on monitoring procedures for collecting detailed data on wetland integrity (Wardrop et al., 2007a,b). Nevertheless, the models used in the "three-tier" approach are statistically rather than physically based, and are not unlikely to be inappropriate for quantitatively evaluating wetland conservation/restoration scenarios.

Trepel and Palmeri (2002) used a score system to select most suitable sites for wetland restoration in the 40 km^2 Neuwührener Au watershed located in northern Germany. The potential effects of the restoration scenarios were evaluated using three different equations that relate nitrogen load with wetland area and/or hydraulic retention time. The results indicated that the restoration in the upland areas will be more efficant than that in the downstream areas. The predicted nitrogen removal efficiency ranged from 20 to 75%. On the other hand, Arheimer and Wittgren (2002) developed a wetland nitrogen removal module and incorporated it into a dynamic process-based watershed model (Lindström et al., 1997). The coupled model was used to evaluate nitrogen removal rates for the 40 potential wetlands within the 224 km^2 Genevadsån watershed in southern Sweden. The modeling showed that for a given wetland, its nitrogen removal rate ranged from 57 to 466 kg ha^{-1} yr^{-1} (i.e., 0.3–27%), depending on the residence time of the wetland. The residence time was computed as a function of the wetland size, hydraulic loading, and nitrogen concentration in inflow.

These two modeling studies aimed to quantify effects of wetland restoration on nitrogen removal only at watershed scale, though it would be ideal to also quantify the aforementioned other effects, including reductions of flood peak, nutrient, and sediment. The first study was based on the long-term average hydrologic conditions and did not consider the dynamics of flow and nitrogen in the wetlands, while the second study only included channel fens (i.e., a network of broad channels that are connected to the basin drainage system). However, general restoration scenarios may usually consist of channel fens as well as flat bogs (Wang et al., 2008). Compared with channel fens, flat bogs typically occur as isolated patches surrounded by peat plateaus. Previous studies (e.g., Leavesley and Stannard, 1995; Padmanabhan and Bengtson, 2001; Leavesley et al., 2002) gave inconsistent results partially due to the tenuous assumption that hydrologic functions of wetlands within a watershed are linearly additive. In contrast, the HEW concept (Wang et al., 2008) can reflect the nonlinear functional relations between runoff and wetlands that were revealed by Quinton et al. (2003), and thus enable accurate simulations of general conservation/restoration scenarios. This concept may also be very useful for the emerging wetland restoration efforts in Europe (e.g., Acreman et al., 2007) and can be integrated with European models (e.g., Hattermann et al., 2006; Förster, 2008).

The objective of this study was to use the HEW concept in SWAT to assess the effects of wetland restoration in the Broughton's Creek watershed located in southwestern Manitoba and the effects of wetland conservation in the Otter Tail River watershed located in northwestern Minnesota. The effects were measured as reductions of flood runoff and loadings of sediment, total phosphorus (TP), and total nitrogen (TN). Hereinafter, TP is expressed as phosphorus element and TN as nitrogen element. These two study areas were selected because they are typical prairie lands and have ongoing wetland conservation/restoration programs (Hart, 1995; DUC, 2007).

2. Description of SWAT and HEW

SWAT is a physically based, continuous-time model that operates on a daily time step and is designed to predict impacts of management practices on water, sediment, and agricultural chemical yields in large ungauged watersheds (Arnold and Fohrer, 2005; Gassman et al., 2007). SWAT is composed of three major components, namely subbasin, reservoir routing, and channel routing, and each of these components includes several subcomponents. For example, the subbasin component consists of eight subcomponents, namely hydrology, weather, sedimentation, soil moisture, crop growth, nutrients, agricultural management, and pesticides. The hydrology subcomponent, in turn, includes surface runoff, lateral subsurface flow, percolation, groundwater flow, snowmelt, evapotranspiration, transmission losses, and ponds/wetlands. Detailed descriptions of the methods used in modeling these components and subcomponents can be found in Arnold et al. (1998), Srinivasan et al. (1998), and Neitsch et al. (2002a). SWAT provides two surface runoff estimation options, namely the SCS-CN method (USDA-NRCS, 2004) and the Green-Ampt equation (Green and Ampt, 1911). Because the latter option requires subdaily data on precipitation and temperatures (Arnold et al., 1998) and has an inconclusive advantage (Rawls and Brakensiek, 1986; Ponce and Hawkins, 1996; King et al., 1999; Kannan et al., 2007), the SCS-CN method was used.

For modeling purposes, SWAT subdivides a watershed into a number of subbasins. Portions of a subbasin that possess unique land use/management/soil attributes are grouped together and defined as one hydrologic response unit (HRU; Neitsch et al., 2002a,b). Depending on data availability and modeling accuracy, one subbasin may have one or several HRUs defined. In SWAT, each subbasin is simulated as a homogenous area in terms of climatic conditions, and each HRU is assumed to be spatially uniform in terms of soils, land use, and topography. In addition, by default, all HRUs within a subbasin are assumed to have a slope steepness and slope length equal to the corresponding average values of the subbasin. As with other studies (e.g., Van Liew et al., 2005; Stewart et al. 2006), this study adopted the default values, although each HRU could have different values.

SWAT treats wetlands as water bodies located within subbasins (Arnold et al., 2001; Neitsch et al., 2002a), and allows one wetland to be modeled for each subbasin. For a subbasin with several wetlands, a HEW can be formulated to have equivalent hydrologic functions with its component (i.e., real) wetlands on the subbasin basis. The HEW is defined in terms of three calibration parameters: the fraction of the subbasin area that drains into the HEW (fr_{imp}), the volume of water stored in the HEW when filled to its normal water level (V_{nor}), and the volume of water stored in the HEW when filled to its maximum water level (V_{mx}). That is, these three parameters should be adjusted to make the predicted flow hydrograph at the inclusive subbasin outlet from using the HEW closely match that from using the component wetlands (Wang et al., 2008).