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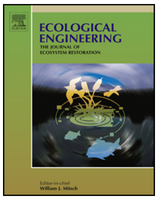

Assessing the significance of wetland restoration scenarios on sediment mitigation plan

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ABSTRACT

Wetlands have many environmental, social, and economic values. However, due to accelerated land use change and lack of understanding of the functions of wetland ecosystems, they have deteriorated, if not been lost in many areas worldwide. Meanwhile, current functional wetland assessment techniques only provide rough estimations, and are in most cases site specific and qualitative. The overall goal of this project is to examine the sediment reduction benefit of wetland implementation scenarios both at subbasin and watershed scales. Two sets of models were used to accomplish this goal. First, a watershed model – the Soil and Water Assessment Tool (SWAT), was employed to estimate sediment load at the subbasin scale. However, due to limitations of wetland functions of SWAT, a second model – the System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) was used. The sediment load generated for each subbasin was incorporated in the SUSTAIN model. This allows for evaluating sediment reduction capability of wetlands at subbasin level. Next, a portion of sediment not treated by a wetland was fed back to the SWAT model and routed to the watershed outlet. The impacts of four different wetland surface areas (0.40, 0.81, 2, and 4 ha) on sediment load mitigation were examined one-at-a-time for all subbasins within the River Raisin watershed located in southeastern Michigan and northeastern Ohio. Comparison of the sediment reductions due to different wetland restoration scenarios reveals the importance of wetland placement in a watershed. In general, the rate of streamflow reduction resulting from wetland implementation is higher than sediment reduction at the subbasin level but more comparable at the watershed level. In addition, clusters of wetlands installed at the distance of 150–200 stream km from the outlet outperformed other clustered wetlands at closer and farther distances. Wetlands associated with 1st order streams performed better at the subbasin level, while wetlands located at 4th order streams performed better at the watershed level. Considering environmental and economic issues of wetland restoration scenarios revealed that the 0.4 ha wetlands were the most suitable for subbasin and watershed level implementation due to its sediment reduction efficiency and significantly lower cost of installation and maintenance.

1. Introduction

Wetlands perform essential hydrological, geochemical, and biological functions at the watershed level (De Laney, 1995; Hart, 1995). They have the capacity to significantly reduce nutrients, sediments, and other pollutant concentrations produced from runoff under different environmental conditions at the watershed scale (Jordan et al., 2003; Arheimer et al., 2004; Skagen et al., 2008; Wang et al., 2010; Fan et al., 2012). Processes that contribute to pollutant removal in wetlands are chemical, physical, and biological in nature (Kadlec, 2008). Chemical processes include precipitation of phosphorus by iron, aluminum or calcium, and precipitation of heavy metals (Nilsson et al., 2011). Additionally, wetlands facilitate chemical transformation of nitrogen, which leads to the release of nitrogen to the atmosphere (Vymazal, 2007). Physically, wetland vegetation substantially slows runoff, leading to deposition of mineral and organic particles and adsorbed contaminants (Carter, 1996). Wetland microbial activity is a biological process that results in decomposition of organic matter and the removal of nitrogen through microbial transformation (nitrification–denitrification)

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(Brix, 1993). Plant uptake of organic chemicals into plant tissue is another biological process attributed to wetlands' ability to treat pollutants (Ryan et al., 1988). Furthermore, wetlands provides many ecosystem services, especially related to water quantity (Luecke, 1993; Comin et al., 1997; Keddy, 2000; Ramsar, 2004). Wetlands are effective in catching, retaining, and filtering runoff water generated from heavy rainfall or snowmelt events and promoting groundwater infiltration, which helps reduce river peakflow (Luecke, 1993; Comin et al., 1997; Keddy, 2000; Ramsar, 2004).

Wetland restoration and construction technologies for the treatment of pollutants is an emerging field (USEPA, 2000; Schröder et al., 2007). A robust understanding of pollutant removal processes and wetland environmental characteristics is needed for conservation, restoration, planning, and design purposes. For this reason wetland water quality improvement capabilities have been studied for different types of wetlands in specific settings, as described above. However, the challenge to optimize ideal restoration conditions on a larger scale persists due to the complexity of wetlands and pollution transport processes at the watershed scale.

Researchers use numerous models to simulate pollutant transport at catchment and watershed scales. The Soil and Water Assessment Tool (SWAT) is one of the most widely used models in watershed and river basin simulation (Gassman et al., 2014). Arnold et al. (2011) used SWAT to simulate the water budget in a constructed wetland in Texas, where the model was modified to include the interaction between ponded water in the wetland and the soil profile and shallow aquifer. Wang et al. (2008) developed the hydrologic equivalent wetland (HEW) method to represent wetlands in SWAT model and applied the method to successfully simulate streamflow in a watershed located in Minnesota. Liu et al. (2008) developed a SWAT extension to simulate flow and sediment in a riparian wetland, but did not validate the model due to the limitation of observed data. Wu and Johnston (2008) compared SWAT performance between forested and a wetland/lake dominated watershed in Michigan, and reported satisfactory model calibration but discrepancies in summer streamflow prediction. Wang et al. (2010) applied the HEW method to estimate streamflow, sediment, total nitrogen (TN), and total phosphorus (TP) loads under wetland restoration and conservation scenarios in Manitoba, Canada. However, the authors only calibrated the model for streamflow. Therefore, evaluation of wetland performance for sediment, TN, and TP is highly uncertain. Feng et al. (2013) incorporated a wetland module into SWAT to simulate wetland hydrology in northeast China, where the method performed well in reconstructing wetland hydrological processes. Martinez-Martinez et al. (2014) used SWAT to simulate streamflow rates and peaks under wetland restoration scenarios and reported that average streamflow fluctuation at the watershed outlet is more sensitive to wetland area than depth. Numerous other researchers have used different modeling approaches to incorporate wetlands in their simulations such as the Hydrological Simulation Program-Fortran (HSPF) (Schwar, 1998 Zhang et al., 2009), MIKE-SHE (Thompson et al., 2004; Zacharias et al., 2005; Dai et al., 2010), DRAINMOD (Caldwell et al., 2007; Skaggs et al., 1995; Jia and Luo, 2009), and SWMM (Obropta et al., 2008; Tsihrintzis et al., 1998; Koo et al., 2013). Overall, most studies have only considered wetland hydrology in watershed scale modeling and have either ignored or not calibrated the model for sediment and nutrients to simulate the impact of wetland restoration scenarios on pollutant treatment, as such a task is still a challenge to scientists (Wang et al., 2008).

Among physically-based watershed/water quality models, SWAT is a comprehensive model that combines spatial and temporal analysis, is open source, and has strong model support, making it one of the most widely used water quality models in watershed and river basin modeling (Gassman et al., 2014; Srinivasan et al., 1998). However, a major drawback of using SWAT for watershed scale wetland modeling is that SWAT assumes a completely mixed wetland system in pollutant routing. In addition, SWAT ignores nutrient transformation in simulating nutrient removal in wetlands, ponds, and reservoirs and considers settling as the sole method of nutrient removal (Neitsch et al., 2011). In order to solve this problem, we proposed to couple SWAT with a second model capable of addressing these issues. The System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) model (Alvi et al., 2009) allows users to simulate wetlands as either a plug flow reactor or a continuously stirred tank reactor (CSTR) in series with a user-defined number of CSTRs. In addition, SUSTAIN models pollutant removal by either first-order order decay or a modified kinetic model (K–C^*) (Shoemaker et al., 2009). This research addresses the challenges of using a hybrid of two water quality models to examine the sediment reduction benefits of wetland implementation scenarios at subbasin and watershed scales. The specific objectives of this project are to: (1) assess the impacts of wetland restorations scenarios on flow and sediment, (2) determine the role of wetland placement in watershed sediment dynamics by considering the distance to the outlet and stream order concept, and (3) evaluate the environmental and economic aspects of wetland restoration scenarios at the subbasin and watershed scale.

2. Materials and methods

2.1. Study area

The River Raisin watershed (Hydrologic Unit Code 04100002) is located primarily in southeastern Michigan, with a small portion located in northern Ohio (Fig. 1). The River Raisin watershed drains approximately 2681 km^2 into Lake Erie. The watershed is predominantly agricultural, covering approximately 66% of the total watershed area (CDL, 2012). The primary crops grown in the watershed are corn, soybeans, and wheat. The remaining land cover is 13% forest, 12% urban, 7% wetlands, 1% range grasses, and 1% water (CDL, 2012).

The River Raisin watershed is characterized by hilly to moderately rolling topography in the western and northwestern regions and by relatively flat terrain in the southeast. Soils are characterized as having land slopes of 0–5 percent (Knutilla and Allen, 1975). Sandy loams, loams, and clay loam soils with moderate to high infiltration rates dominate the upstream northwestern portion of the River Raisin watershed. The streams in this portion of the watershed have more stable flows and consistent groundwater recharge. Meanwhile, the southeastern portion of the watershed is dominated by primarily clays, clay loams, and silty clays with low to very low permeability and slow infiltration rates (Dodge, 1998).

The River Raisin watershed was selected due to its significant variation in soil types, land use patterns, topography and geology. Historically, this watershed was a swamp (wetland) with flat topography and muck (highly decomposed organic materials) and clay soils (Dodge, 1998). Comparison of the current land use map (NLCD, 2001) with prehistoric land use (MNFI, 2014) reveals a loss of 59% of the woody wetlands and 91% of emergent herbaceous wetlands since the mid-1800s. Due to land use changes (extensive tile drainage) the watershed is now highly agricultural.

2.2. Models

Wetlands are complex, diverse, and dynamic ecosystems, and watershed-scale wetland assessment is a challenge currently faced