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Modeling the hydrological significance of wetland restoration scenarios

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ABSTRACT

Wetlands provide multiple socio-economic benefits, among them mitigating flood through short- and long-term water storage functions and assisting with reduction of downstream flood peaks. However, their effectiveness in controlling floods is dictated by wetland size and distribution within a watershed. Due to the complexity of wetland hydrological processes at the watershed scale, the Soil and Water Assessment Tool (SWAT) was used to study the impact of wetland restoration on streamflow rates and peaks in the Shiawassee River watershed of Michigan. Wetland restoration scenarios were developed based on combinations of wetland area (50, 100, 250, and 500 ha) and wetland depth (15, 30, 61, and 91 cm). Increasing wetland area, rather than depth, had a greater impact on long-term average daily streamflow. Wetland implementation resulted in negligible reductions in daily peak flow rates and frequency of peak flow events at the watershed outlet. In developing high impact areas for wetland restoration, similar locations were identified for reduction of subbasin and watershed outlet streamflow. However, the best combinations of area/depth differed depending on the goal of the restoration plan.

1. Introduction

Wetlands play a diverse, unique, and important role in the health and conservation of vital ecosystems. Wetland systems directly support millions of people throughout the world by providing such benefits as fertile soils for agricultural production (food and fiber), wildlife habitat, clean water, trees for timber and fuel, and recreation areas. In addition, wetlands provide important hydrologic, geochemical, and biological functions in a watershed (De Laney, 1995; Hart, 1995; NRC, 1995; Acreman and Holden, 2013; Ranieri et al., 2013). For example, wetlands have the ability to retain surface floodwaters, releasing the excess water slowly to downstream areas, while wetland soil provides a considerable amount of floodwater mitigation, holding three to nine times the weight of the soil per unit volume (Jiang et al., 2007).

Meanwhile, wetlands are an extremely vulnerable environmental system and have significantly vanished in the past century (Nejadhashemi et al., 2012). According to Dahl (2000), approximately 2606 km^2 of wetlands were lost in the United States between 1986 and 1997 with an estimated loss distribution of: urban development (30%), agriculture (26%), silviculture (23%) and rural development (21%). Furthermore, in recent years, wetlands in the U.S. are disappearing at a rapid rate of 243 km^2 per year (Dahl, 1990, 2000). Some examples of the possible major causes of wetland losses and degradation in the United States are: artificial drainage, deposition of fill material, diking and damming, conversion to crop production, construction, induced erosion, changing nutrient levels, increases in urbanization, and natural causes such as erosion, droughts, hurricanes and climate change (Carter, 1961; Leopold, 1968; U.S. EPA, 1993; Wray et al., 1995; Burkett and Kusler, 2000; U.S. EPA, 2009).

To protect wetlands, various regulations have been developed. One example is the Clean Water Act (CWA), administered by the United States Environmental Protection Agency (EPA). The CWA Section 404 established a program to regulate the discharge of dredged and fill material into waters of the United States, including wetlands (Copeland, 2006). In addition, many efforts have been developed to conserve, preserve, and restore wetlands. These efforts include the development and use of tools to identify wetland restoration and conservation areas, demonstrate wetland services, and perform wetlands classifications. Although some studies have attempted to describe wetland functions using

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watershed models (Konyha et al., 1995; Reinelt and Horner, 1995; Hawk et al., 1999; Arnold et al., 2001; Kirk et al., 2004; Zhang and Mitsch, 2005; Liu et al., 2008, Wang et al., 2008; Melles et al., 2010; Yang et al., 2010), there are limitations primarily in oversimplification of wetland processes and understanding flood mitigation benefits based on wetland placement in a watershed (Drexier et al., 1999; Raisin et al., 1999; Wang et al., 2008; Yang et al., 2008). Efforts to simulate wetlands at the watershed scale are discussed below.

Conan et al. (2003) found that the Soil and Water Assessment Tool (SWAT) adequately simulated land use change from wetlands to dry land in Spain (Upper Guadiana river basin). The model represented the impact of groundwater withdrawals throughout the basin and showed misrepresentation of certain conditions that could be related to lack of sufficient data (e.g. rainfall data). Wu and Johnston (2008) performed a hydrologic comparison between a forested and a wetland/lake dominated watershed in northern Michigan using SWAT. The specific objective was to compare the effects of wetland and lake abundance on the magnitude and timing of streamflow from two watersheds (east and middle branches of the Ontonagon River basin). The study showed that the watershed containing greater wetland and lake areas had lower spring peaks and higher sustained flows during summer and fall. Wang et al. (2010) simulated the effects of wetland conservation and restoration on water quality and quantity for a 4506 km^2 watershed in Minnesota. In this study, the concept of hydrologic equivalent wetlands (HEWs) was utilized. A HEW was defined in terms of six calibrated parameters: fraction of the subbasin area that drains into wetlands, volume of water stored in the wetlands when filled to their normal water level, volume of water stored in the wetlands when filled to their maximum water level, longest tributary channel length in the subbasin, Manning's n value for the tributary channels, and Manning's n value for the main channel (Wang et al., 2008). This study showed that the HEW concept allows non-linear functional relations between watershed processes and wetland characteristics (e.g. morphology). A reduction of approximately 10–20% of the wetlands in the study area resulted in a considerable increase in peak discharge. They concluded that wetland conservation is a higher priority than wetland restoration (Wang et al., 2010). Yang et al. (2008) studied water quantity and quality benefits from wetland conservation and restoration scenarios using SWAT in the Broughton's Creek watershed (251 km^2). Multiple wetland restoration scenarios were examined, including: 0%, 10%, 25%, 50%, 75%, 90% and 100%. The optimal scenario determined for peak flow reduction in this study was 90% restoration. However, when compared with cost effectiveness, scenarios ranging from 50% to 80% were the most cost effective in terms of the benefit to the wetland acreage ratios. Hattermann et al. (2008) compared two approaches that allow integration of important wetland processes using the Soil and Water Integrated Model (SWIM). They compared a simple supply/demand approach versus an advanced hydrotropes approach and concluded that using the advanced approach significantly improved seasonal river discharge in catchments with wetlands.

Placement of a wetland for streamflow reduction is an important consideration in the planning process. Understanding the relationship between stream order and wetland area and depth allow for targeting stretches of river in a watershed in which restoration will be most beneficial when project goals involve streamflow reduction. As described above, a number of studies have explored watershed-scale wetland modeling. However, none of these studies systematically examined the impact of wetland area, depth, and placement on streamflow and peak flow reduction in a watershed. This study is also unique in terms of the number of scenarios and the length of study performed to assess the hydrological function of wetlands. The Shiawassee River watershed was selected for planning of wetland conservation activities because historically, the majority of the watershed was covered by wetlands (57%). However, vast land use change has reduced the wetland area to 11% of the watershed. Therefore, this watershed was considered to be a good candidate for development of wetland conservation and restoration strategies. The hypothesis is that by introducing wetlands onto the landscape, we can significantly reduce peak flow rate, which ultimately decreases environmental and economical losses due to flooding.

We utilize SWAT to evaluate the impacts of wetland depth (15, 30, 61, and 91 cm), wetland area (50, 100, 250, 500 ha), and wetland placement in the watershed on streamflow and peak flow reduction at the watershed scale. The findings of this study will provide scientific understanding of wetland functions in controlling and altering the hydrologic cycle of a watershed.

2. Materials and methods

2.1. Study area

The Shiawassee River watershed (hydrologic unit code 04080203) is located southwest of Saginaw Bay in the central portion of Michigan's Lower Peninsula and is part of the Saginaw watershed (Fig. 1). It drains approximately 3000 km^2 through the Shiawassee River to the Saginaw River, which ultimately drains to the Saginaw Bay of Lake Huron.

The land use in the Shiawassee River watershed during presettlement was composed by approximately 57% woody wetlands and approximately 38% of deciduous/mixed forest (Apfelbaum et al., 2007). Currently, land use in the watershed is 57% agricultural (primarily corn, soybean, wheat, and pasture), 14% deciduous/mixed forest, 11% woody wetlands, 7% grassland, and 5% urban (Fig. 2). Primary land use change in the watershed was the conversion from marshes, forested bog wetlands and mixed/deciduous forests into agricultural land by logging, filling and draining (tiling) wetland areas.

In the Shiawassee River watershed, flooding has historically resulted in loss of agricultural commodities and displacement of native wildlife. A comprehensive flood analysis for the Shiawassee River watershed was performed by the Michigan Department of Natural Resources and Environment (Fongers, 2010). The watershed is both a storm-driven and snowmelt-driven system, which results in considerable flooding during the growing season, while storm-driven system and rain-on-snow events generate significant streamflow increases. According to Fongers (2010), the annual exceedance probability for a 100-year return period is 150 m^3/s at USGS gauging station 04144500 (Fig. 1).

2.2. Soil and water assessment tool

2.2.1. SWAT model description

The SWAT model is a watershed scale model developed by the US Department of Agriculture (USDA)-Agricultural Research Service (Arnold et al., 1998). In this study ArcSWAT2009.93.7a was used. SWAT has proven to be a robust model capable of predicting impacts of land use change and management practices on water, sediment, and agricultural chemical yields in large un-gauged watersheds over long periods of time (Gassman et al., 2007). The model features include watershed hydrology, sediment and water quality modeling, pesticide fate and transport simulation, channel erosion simulation, and rural and agricultural management practices (e.g. agricultural land planting, tillage, irrigation, fertilization, among other). SWAT subdivides a watershed into a number of