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On comparison of peak flow reductions, flood inundation maps, and velocity maps in evaluating effects of restored wetlands on channel flooding

Amir Javaheri *, Meghna Babbar-Sebens

School of Civil and Construction Engineering, Oregon State University, Corvallis, OR, USA

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A B S T R A C T

With growing interest in using restored and/or new constructed wetlands as additional flood mitigation systems, it has become essential to investigate the effectiveness of wetlands in reducing the risk of flood hazards. This study examines and compares evaluation techniques based on peak flow estimation, flood inundation area estimation, and velocity maps to assess the performance of wetlands in reducing flood hazards in a Midwestern watershed affected by changing precipitation patterns. School Branch, one of the main branches of Eagle Creek watershed, located in central Indiana, was selected as a study area. A coupled hydrologic-hydraulic model approach was proposed to simulate the outflow generated by various design storms. Then the water profile and water velocity in the river were calculated and finally the inundation and velocity maps were generated. Also, the effect timing of storm on runoff modulated by wetlands was investigated by applying design storms to different months of year. The results of this study show that wetlands can reduce the peak flow up to 42%, flood areas up to 55% and maximum velocity up to 15%. Additionally, a sub-basin that had maximum peak flow reduction for a specific design storm did not necessarily have a simultaneous maximum reduction in flood inundation area, indicating the variability in how wetlands mitigate flooding in different sub-basins of a watershed. Also, deeper wetlands are more effective in reducing the impacts of storms with higher return periods. For example, at the study site, deeper wetlands ($D = 1.8$ m) were able to reduce peak flows up to 20% for a 500 year storm whereas shallow wetlands ($D = 0.5$ m) reduced the peak flow by 11% for the same storm.

1. Introduction

Flooding is one of the most destructive natural disasters in the United States with annual damages as high as approximately \$2.9 billion (FEMA, 2013). States in the Mississippi River Basin have been particularly susceptible to flooding over the last few years. For example, the Midwestern state of Indiana has experienced several severe floods in recent years, such as floods in June 2008 and April 2013. In June 2008, the rainfall was measured from 5 to 11 inches (www.NOAA.gov) which affected more than 40 counties in Indiana. This flood event is considered as the largest agriculture disaster affecting 9% of the state's farmland (Carter et al., 2008). In April 2013, 4–7 inches (www.NOAA.gov) rainfall happened in central Indiana. The USGS station at Zionsville recorded a peak discharge of 17,400 f^3/s during this flood which is higher than a 500-yr flood estimated for this area (Rao, 2006). These recent flooding events (e.g. 2008 and 2013 floods) have indicated that efforts beyond existing levees, dams, etc. are needed for increasing current watershed capacities to mitigate impacts of floods.

Wetland ecosystems have been proposed as potential ecological solutions to reduce runoff and decrease risk of downstream flooding (Hey et al., 2004; Mitsch and Day 2006; Lemke and Richmond, 2009). Riparian and upland wetlands reduce velocity and temporarily store water away from the rivers, thereby reducing and delaying peak flows (Baker and Van Eijk, 2006). In addition to flood benefits, wetlands improve water quality, preserve the native flora, and create habitats for the fauna (Peterjohn and Correl, 1984; D'Arcy and Frost, 2001; Bekele and Nicklow, 2005). However, current modeling studies that have investigated effectiveness of wetlands in reducing flooding impacts have been based on using reduction in peak flows to estimate wetland performance (e.g., Ogawa and Male, 1986; Kaini et al., 2007; Cohen and Brown, 2007; Babbar-Sebens et al., 2013). For example, Kaini et al. (2007) coupled a single-objective genetic

* Corresponding author at: 233 Owen Hall, School of Civil and Construction Engineering, Oregon State University, Corvallis, OR, USA. Tel.: +1 541 737 4934.
E-mail addresses: javaheam@onid.oregonstate.edu (A. Javaheri), meghna@oregonstate.edu (M. Babbar-Sebens).

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algorithm (GA) with the soil and water assessment tool (SWAT; Arnold et al., 2001, 2005) to find the best combination of pond sizes in sub-basins across the watershed that minimized maximum daily peak flow, while also constraining the maximum areas of ponds within a user-defined upper limit. They were able to attain an estimated reduction of 16.8% in maximum daily flows with the optimal distribution of ponds found for their watershed site (Silver Creek watershed in Illinois). Babbar-Sebens et al. (2013) developed a GIS-based watershed-scale methodology for first identifying potential sites and maximum areas of wetlands in a tile-drained landscape, and then optimized the spatial distribution, wetland areas, and drainage areas of these potential wetlands to attain maximum reduction in peak runoff flows in the entire watershed. They also used a coupled optimization (NSGA-II; Deb et al., 2002) and hydrologic model (SWAT) to find their optimal spatial-plans for creating/restoring potential wetlands, and were able to achieve significant peak flow reductions of 20% or higher with fewer sites and smaller wetlands. However, none of these research articles have assessed how effective the distribution of wetlands in their optimal plans would be in reducing flood inundation areas and stream velocities in the channel network. Flood inundation and velocity maps are beneficial for flood hazard studies, and are usually estimated by hydraulic models of channels (e.g., Sarhadi et al., 2012 Aggett and Wilson, 2009; Sanders, 2007; Horritt and Bates, 2002). For example, Sarhadi et al. (2012) used regional flood frequency analysis to estimate flood quantiles in different return periods for ungaged rivers, and then used 1D steady state subcritical hydraulic model to create flood inundation maps for a watershed located in Iran. Aggett and Wilson (2009) developed a high-resolution digital terrain model (DTM) and one-dimensional hydraulic model to investigate the avulsion hazard area using flood inundation, velocity and shear stress maps. Alaghmand et al. (2010) generated flood hazard maps based on flood inundation and velocity maps by developing coupled hydrologic and hydraulic models. The authors are not aware of any reported study that have investigated the performance of new wetlands based on such inundation and velocity maps estimated by coupled hydrologic-hydraulic models.

The main goal of this study is to propose and compare performance methods based on peak flow reduction, inundation area reduction, and velocity reduction to evaluate the effectiveness of wetlands in reducing flood hazards in a watershed. Additionally, this study also investigates how timing of extreme rainfall events affects the performance of wetlands in mitigating runoff. The remainder of the paper is organized in the following sections: Section 2 on methodology that describes the study area, proposed modeling framework, and calibration of the constituent hydrologic and hydraulic models, Section 3 describes the results of various experiments conducted in this study, and finally Section 4 which provides concluding remarks.

2. Methodology

2.1. Study area

The Eagle Creek Watershed (Fig. 1), with a catchment area of about 419 km^2 above the Eagle Creek reservoir, is situated northwest of the city of Indianapolis, Indiana, USA. The Eagle Creek Reservoir is one of the main sources of drinking water for the region and was originally built in 1967 for flood control. The elevation in the watershed varies from 300 m above sea level in Fishback Creek sub-basin to 240 m above sea level in the School Branch. About 60% of the land-use of watershed is used for

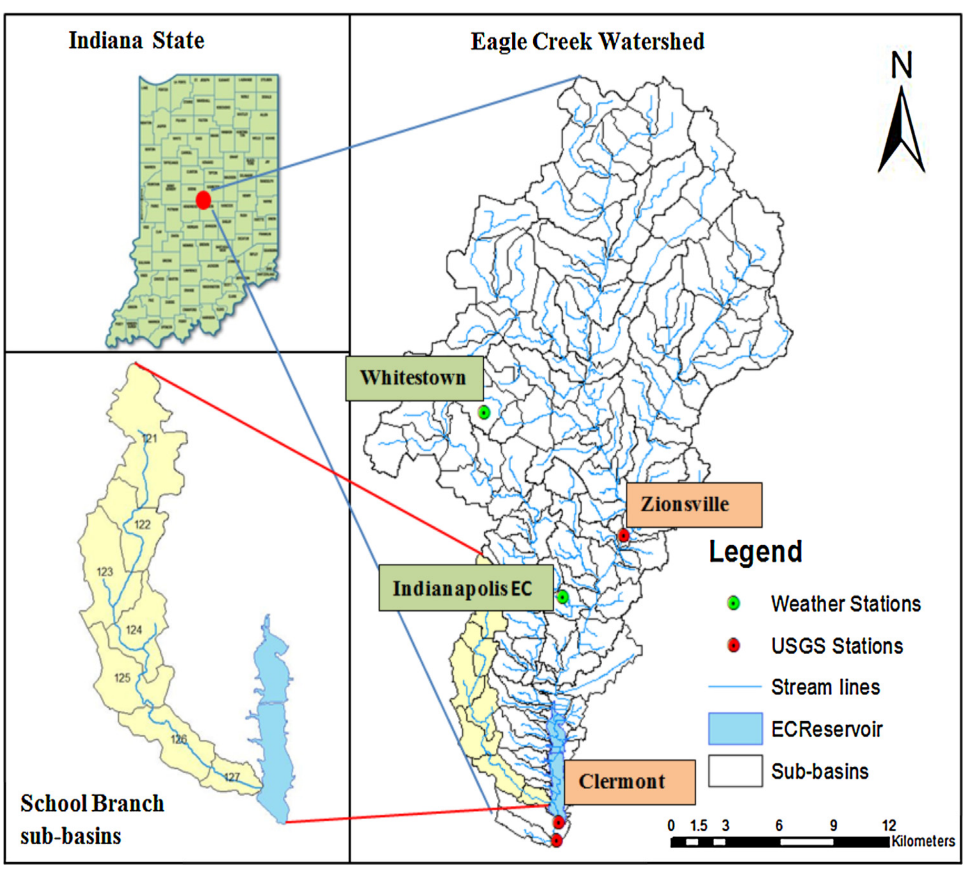

Fig. 1. Streams and sub-watersheds of the Eagle Creek Watershed, IN, USA.