Ecological Engineering 89 (2016) 80–102

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Using climate change scenarios to evaluate future effectiveness of potential wetlands in mitigating high flows in a Midwestern U.S. watershed

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ARTICLE INFO

Article history:
Received 25 November 2014
Received in revised form 1 November 2015
Accepted 23 January 2016
Available online 7 February 2016

Keywords:
Wetlands
Hydrology
Climate change
NARCCAP
SWAT
Bias correction

ABSTRACT

The Midwestern United States have seen increased flooding and droughts from climate change, urban development, deforestation, and wetlands removal. Adding new wetlands in the landscape have been proposed as a conservation strategy, especially in tile-drained agricultural watersheds, to increase upland storage of runoff and reduce peak flows. The goal of this study was to evaluate the long-term performance of a set of potential wetlands identified in the Eagle Creek Watershed in central Indiana, U.S., to reduce a range of high flows estimated from future climate scenarios. The Soil and Water Assessment Tool model was forced with bias-corrected climate projections from the North American Regional Climate Change Assessment Program to evaluate the impacts of climate change on watershed hydrology and peak flows. The ensemble of climate projections predicted both increase and decrease in magnitudes of the 5% exceedance flow from the past (1971–2000) to the future (2041–2070) time period. However, the model predicted that if the potential wetlands existed in these time periods then the magnitude of the 5% exceedance flow would be reduced by approximately 0.5–1.5 m^3/s across all climate projections and for both the past and future periods. These identified potential wetlands, which occupied only approximately 1.5% of the watershed area but received runoff from approximately 29% of the watershed area, were also found to reduce peak flows by up to 20–60 m^3/s (i.e., 15–20% of the reference peak flows for a watershed without these wetlands). The wetlands were also found to decrease the frequency of high peak flows. Wetlands proved to be a robust solution for peak flow reduction, producing consistent reductions from the past to future time periods and across all climate projections. The methodology used in this study to incorporate climate change into hydrologic models to evaluate conservation practices could also be applied to other watersheds and other conservation practices for better long-term watershed management decisions.

1. Introduction

The frequency of extreme rainfall events has increased over the last century in multiple regions of the world, and is predicted to continue to increase, causing increased flooding risks, erosion, and water quality degradation (U.S. Global Change Research Program, 2014; IPCC, 2014). Midwestern watersheds in the United States have already begun to see an increase in early spring runoff and peak flows, and can expect 10–20% more runoff in 2041–2070 relative to 1971–2000 due to climate change (U.S. Global Change Research Program, 2014). In addition, multiple watersheds in Indiana and rest of Midwestern states have also experienced loss of diverse ecosystem services provided by watersheds because of land alterations, including deforestation, artificial agricultural drainage system, and urbanization. The climate and land use changes have resulted in an altered hydrologic cycle, as seen by earlier snowmelt runoff events, lower late-summer flows, more severe floods and droughts, and increased sediment and water quality problems. For example, in the year 2011 Indiana experienced record-breaking heat in 7 counties, record-breaking rainfall in 22 counties and record-breaking snowfall in 6 counties, resulting in a total of 12 broken heat records, 31 broken rainfall records, and 10 broken snowfall records (Natural Resources Defense Council (NRDC), 2012). The state has been declared a flood-disaster area 14 times between 2000 and 2011 from severe storms (Federal Emergency Management Agency (FEMA), 2014), where as in the period between 1989 and 1999 the state was declared only four times as flood disaster area.

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http://dx.doi.org/10.1016/j.ecoleng.2016.01.014

Based on current observations and climate change projections, the state can expect continued changes and worsening impacts (U.S. Global Change Research Program, 2014).

Restoration and construction of new wetlands have been proposed as alternatives to support existing structural solutions that mitigate flooding and regulate streamflows (Heisel, 2009; Hey et al., 2009; Mitsch and Day, 2006; Wilson, 2009; Zedler, 2003). Hey et al. (2009) stated that restoration of wetlands in floodplains would provide additional storage for flood waters on the Mississippi River above Grafton, IL. They further reported that the 1993 flood would have filled 33% and the 2008 flood would have filled only 7% of the 100-year floodplain. In addition, the wetland area that would be needed to store the flood water from the 1993 flood would have only taken up only 4% of the total watershed area. Wetlands not only reduce peak streamflows by storing water away from the channel and slowly releasing it, but also improve water quality and provide wildlife habitat (Keddy, 2010; Moshiri, 1993). Heisel (2009) suggests an integrated management strategy to tie ecological restoration projects with flood control projects. Mitsch and Day (2006) found that constructing wetlands between farms and adjacent streams or diverting river water into wetlands along major channels in the Mississippi–Ohio–Missouri River basin could also lead to substantial reductions in nitrogen loads in the river, in addition to providing flood control benefits. By restoring or constructing wetland areas, many of the long-term goals for this region could be met, including, increase in upland storage capacities, improvement in infiltration and groundwater recharge, reestablishment of natural flows, and improvements in water quality, wildlife habitat, and overall watershed health.

While the benefits of wetlands are well documented (Hey et al., 2009; Keddy, 2010; Mitsch and Day, 2006; Moshiri, 1993; Zedler, 2003), most existing climate-change related studies have investigated the negative impacts of climate change on existing wetlands. Using rule-based simulation models of hydrology and vegetation dynamics, studies have assessed how current stresses (such, as water quality issues) and man-made alterations (such as, drainage of wetlands for agriculture or construction or dikes and levees) will cause wetland functions to be more sensitive to climate change (Burkett and Kusler, 2000; Poiani et al., 1995). Many studies have concluded that wetlands will likely see increased drying, reductions in wetland size, degradation of wetland habitat, increased demand for agriculture and irrigation water due to less available water, plants and wildlife species destruction, and gas emissions in future climates (Burkett and Kusler, 2000; Johnson et al., 2005; Winter, 2000). The loss of wetlands due to future climate change will be challenging to contain (Hartig et al., 1997) and Hannah et al. (2002) advise that wetlands and protected areas will need to be supplemented with the creation of more wetland areas to withstand the effects of climate change and continue to provide streamflow management benefits.

However, there is a critical lack of research that evaluates how effective additional new wetlands on the landscape will be in mitigating impacts of expected extreme events (e.g., flooding and droughts) from changing climate, and how assessment methodologies incorporating climate change models and their results can be integrated into wetlands planning and management decisions. Previous research conducted in the Eagle Creek Watershed study area in Indiana (Babbar-Sebens et al., 2013) identified multiple potential wetland locations through which flooding benefits could be achieved via new restored/constructed wetlands. Babbar-Sebens et al. (2013) developed a GIS-based methodology for identifying possible upland wetland locations, and used a coupled hydrological model and optimization technique to optimize the spatial distribution of wetlands for upland storage and peak flow reductions. This study, however, used a hydrological model based on current climate input, providing shorter-term results and solutions. In a policy paper bringing light to the need to study how wetland restoration will change in future climates, Erwin (2009) encourages researchers to study wetlands in their spatial context within a watershed and stresses the importance of investigating climate change impacts when developing future wetland restoration initiatives. Erwin (2009) suggests a shift to using three-dimensional modeling techniques (e.g. MIKE SHE) to simulate integrated surface water, groundwater, land use, topographic and hydrological characteristics, and warns that if climate change and variability is not incorporated into medium and long range planning, the success of conservation plans will likely be reduced.

The study presented here evaluates the impacts of climate change on wetland management plans and develops a methodology for creating longer-term wetland restoration plans focused on flood mitigation benefits of wetlands. This research builds on the previous study by Babbar-Sebens et al. (2013) to examine how potential wetlands can be used to mitigate the expected impacts of climate change, but, as Erwin (2009) suggests, focuses on incorporating climate change into long range planning with wetlands. To assess wetland performance in future climate scenarios, the watershed was simulated using a hydrological model forced with climate data dynamically downscaled from an ensemble of global climate models. The main objective of this research was to assess the long term performance of potential wetlands in a Midwestern watershed in reducing peak stream flows in the future, based on available climate change data. Secondary goals for this study were to evaluate the use of climate projection data from the North American Regional Climate Change Assessment Program (NARCCAP) for use in hydrological impact modeling projects, assess urban development land use change impacts, and evaluate expected hydrological impacts of projected climate change in the test watershed.

2. Data and model description

2.1. Study area

Eagle Creek Watershed is primarily an agricultural watershed in Indiana. The Eagle Creek Watershed was selected for this study because of previous relevant work done in the area and supporting infrastructure for wetland planning. Extensive data has been collected for this area, multiple versions of hydrologic models have been developed and tested for the watershed, successful partnerships with stakeholders, including land owners, watershed alliance, federal and local agencies, exist, and an active program for long-term design of conservation practices is present.

The Eagle Creek Watershed is located in central Indiana, about 16 km northwest of Indianapolis. It is part of the Upper White River Watershed and is located in Boone, Hamilton, Hendricks, and Marion counties. The watershed has a drainage area of about 420 square km and drains to the Eagle Creek Reservoir, which provides drinking water to Indianapolis, as well as serves recreational and flood control uses (Fig. 1). The reservoir was constructed to mitigate the seasonal flood inundation in northwest Indianapolis, but has since become impaired by sediments, pesticides, and fertilizers from the agricultural land upstream (Piemonti et al., 2013). The watershed has been delineated into 130 sub-basins for modeling purposes, each containing an individual stream or channel reach connecting it to the next sub-basin. The topography of the land is flat to undulating, with elevations ranging from 240 to 299 m above sea level. The soils are generally productive soils developed in glacial till and loess. The primary land use for the watershed is agriculture (approximately 60%, located in the northwest area of the watershed) with the main crops being corn and soybean. The southeast region has more urban development due to population growth in Indianapolis and increases in urban/suburban infrastructure.