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Application of analytical hierarchy process for effective selection of agricultural best management practices

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ABSTRACT

In this study an analytical hierarchy process (AHP) was used for ranking best management practices (BMPs) in the Saginaw River Watershed based on environmental, economic and social factors. Three spatial targeting methods were used for placement of BMPs on critical source areas (CSAs). The environment factors include sediment, total nitrogen, and total phosphorus reductions at the subbasin level and the watershed outlet. Economic factors were based on total BMP cost, including installation, maintenance, and opportunity costs. Social factors were divided into three favorability rankings (most favorable, moderately favorable, and least favorable) based on area allocated to each BMP. Equal weights (1/3) were considered for the three main factors while calculating the BMP rank by AHP. In this study three scenarios were compared. A comprehensive approach in which environmental, economic, and social aspects are simultaneously considered (*Scenario 1*) versus more traditional approaches in which both environmental and economic aspects were considered (*Scenario 2*) or only environmental aspects (sediment, TN, and TP) were considered (*Scenario 3*). In *Scenario 1*, only stripcropping (moderately favorable) was selected on all CSAs at the subbasin level, whereas stripcropping (49–69% of CSAs) and residue management (most favorable, 31–51% of CSAs) were selected by AHP based on the watershed outlet and three spatial targeting methods. In *Scenario 2*, native grass was eliminated by moderately preferable BMPs (stripcropping) both at the subbasin and watershed outlet levels due the lower BMP implementations cost compared to native grass. Finally, in *Scenario 3*, at subbasin level, the least socially preferable BMP (native grass) was selected in 100% of CSAs due to greater pollution reduction capacity compared to other BMPs. At watershed level, nearly 50% the CSAs selected stripcropping, and the remaining 50% of CSAs selected native grass and residue management equally.

1. Introduction

Nonpoint source (NPS) pollution is the primary source of water quality problems in the United States (USEPA, 2003). In the past few decades, NPS pollution generated from agricultural activities have become the primary contributor to water quality impairments in rivers and lakes (USEPA, 2005). Higher agricultural yields obtained by increasing nutrient application have resulted in environmental concerns such as eutrophication (Shen et al., 2013). Additionally, in order to meet energy security needs, the rapid growth of bioenergy crop production will likely jeopardize aquatic ecosystems (Love et al., 2011; Yousefpour, 2013).

Implementing best management practices (BMPs) on agricultural lands to improve water quality is a well-known method (Giri et al., 2012a). However, BMP performance depends on the BMP placement, timing, and selection procedures (Giri et al., 2012b). Effective BMP implementation strategies cannot be achieved without simultaneous consideration of economic and social aspects of these strategies. To address these concerns, watershed management decision-making plans should consist of evaluating, balancing, and making trade-offs between these components and available alternative management practices (Kaplowitz and Lupi, 2012). Multi-criteria decision analysis (MCDA) is a widely accepted method to address these challenges (Yatsalo et al., 2007). For example, Xu and Mage (2001) investigated agroecosystem health in southern Ontario using multi-criteria analysis. Agroecosystem health was further divided into structural health (change in agricultural land availability), functional health (change in landuse productivity), organizational health (landuse self-dependence), and dynamics (stability, resilience, and capacity to respond to changes in the system over time). They concluded that a holistic approach, rather than a sectoral approach, provides a better understanding of agroecosystem health. Conway (1987) characterized agroecosystems using a number of dynamic properties for

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design and evaluation of agricultural development studies. The agroecosystems were evaluated based on ecological and social criteria. The ecological criteria were productivity, stability, and sustainability, while the social criterion was equitability. The trade-off between these criteria demonstrated the agricultural development.

The multi-attribute utility theory (MAUT), multi-attribute value theory (MAVT), and analytical hierarchy process (AHP) are examples of MCDA methods, which use optimization algorithms to solve complex decision-making problems (Linkov and Steevens, 2013). In particular, AHP uses systematic evaluation criteria based on pairwise comparison and expert knowledge (Young et al., 2009).

Several studies in water resources have used AHP to support decision-making. Young et al. (2009) introduced AHP for selection of BMPs to reduce pollutant loadings downstream from a small parking lot in a residential/commercial development area. The selection of BMP ranking was obtained through pairwise comparison of selection criteria, BMPs among themselves, and BMPs against selection criteria (aesthetic benefit, limiting the BMP installation site to less than one acre, total suspended solid removal, total phosphorus removal, and total nitrogen removal). The pairwise comparison of selection criteria generated a criteria priority vector, while the pairwise comparison of BMPs produced a BMP decision matrix. Finally, the BMP decision matrix was multiplied by the criteria priority vector to generate the priority BMP ranking. The final ranking of BMPs suggested bioretention, porous pavement, and storm water filtering systems were the most effective BMPs in descending order. Calizaya et al. (2010) used AHP to solve MCDA and to identify a sustainable water resources management plan in the Lake Poopo basin, Bolivia. The MCDA structure consisted of three major objectives (economic, social, and environmental issues), 10 conflicts (lower level objectives and sub-criteria), seven instruments to solve the conflicts (alternatives), and implementing actors (organizations). They evaluated the solutions from the MCDA based on the active participation of stakeholders. Forty five pairwise comparisons were included in the MCDA structure. The weights used in this study for environmental, social, and economic criteria were 0.62, 0.33, and 0.06, respectively, and were obtained by stakeholder considerations. The most effective instruments of this MCDA structure were educational training program, formation of local water management organizations, and stakeholder involvement; whereas the most effective implementing actor was local government. Garfi et al. (2011) used AHP in multi-criteria analysis (MCA) to improve strategic environmental assessment of water programs in developing countries and validated for a semi-arid region in Brazil. Both general and specific criteria were selected to determine the best alternative among the One Million Cisterns Project and the Spring Assessment Program for water management. The goal of the study was to improve drinking water supplies to communities living in a semi-arid region. The final criteria were further divided into 11 general sub-criteria for human development and 12 technical sub-criteria for water supply. The relative weights were determined by pairwise comparison among the sub-criteria of each respective group. The results of this study showed that the Cisterns Project were more effective compared to the Spring Assessment Program considering economic, social, political, and environmental aspects. Vadrevu et al. (2008) examined agroecosystem health in Wooster, Ohio using soil health, biodiversity, topography, farm economics, land economics, and social organization. They analyzed the different data such as remote sensing, digital elevation models, soil maps, county auditor records, and land owner questionnaires in AHP to calculate an agroecosystem health index. The final index for each parameter was calculated by combining the key variables determined at the pixel scale.

A number of studies have applied AHP for decision support in water resources, a few of which have used AHP to determine the most effective BMP implementation, primarily in urban areas (e.g. Kaplowitz and Lupi, 2012). However, this study is unique because it focuses on evaluating suitable application of BMPs on agricultural lands on a large scale, which to the best of our knowledge has not been done. The specific objectives for this study were to: (1) evaluate the cost of pollution reduction associated with BMP installation both at subbasin level and the watershed outlet and (2) identify the best BMP type and implementation site using AHP while considering social, economic, and environmental issues based on different spatial targeting methods.

2. Materials and methods

2.1. Study area

This study was conducted on the Saginaw River Watershed (SRW), which is located in east central Michigan (Fig. 1). This watershed was selected because the Saginaw Bay is listed as an Area of Concern by the US Environmental Protection Agency due to high amounts of soil erosion, excessive nitrogen and phosphorus, and contaminated sediments. It consists of six subwatersheds: Tittabawassee, Shiawassee, Pine, Flint, Cass, and Saginaw. This watershed is one of the most diverse watersheds in Michigan, consisting of agriculture, manufacturing, tourism, wildlife habitat, and outdoor recreation (Giri et al., 2012a). The Saginaw River and its tributaries drain into the Saginaw Bay of Lake Huron. This watershed contains nation's largest contiguous freshwater coastal wetland (USEPA, 2009). The mean, minimum, and maximum watershed elevations are 242 m, 177 m, and 457 m, respectively. The total watershed area is 15,263 km^2, of which 42% forest, 23% agriculture, 17% pasture, 11% wetland, and 7% urban. It is one of the predominant agricultural-based watersheds in Michigan, with predominantly corn and soybean cropping rotations.

2.2. Model description

In order to evaluate the BMP effectiveness in reducing NPS pollution in the SRW, a physically based, spatially distributed, watershed-scale model (Arnold et al., 1998; Neitsch et al., 2005) known as Soil and Water Assessment Tool (SWAT) was used. Primary model components include hydrology, soil, landuse, plant growth, nutrients, pesticides, management practices, and weather (Gassman et al., 2007). SWAT calculates flow, sediment, nutrients, and pesticides transport both over land and in-stream based on the physiographic, meteorological, and land-management characteristics of the watershed. The watershed is divided into subbasins and further divided into hydrologic response units (HRUs) based on the homogenous landuse, soil type, slope, and management practices.

2.2.1. Data sources

The SWAT model requires input data such as topography, landuse, soil, and stream network. Topography data in the form of digital elevation model (90 m × 90 m) was obtained through the Better Assessment Science Integrating point and Nonpoint Sources (BASINS) software. Landuse data at 56 m resolution 2008 Cropland Data Layer for the watershed was obtained from USDA's National Agricultural Statistics Service (NASS, 2008). To represent the soil characteristics in the watershed, the State Soil Geographic Database (STATSGO) was used, which was developed by the National Cooperative Soil Survey. The stream network in the form of a National Hydrography Dataset was obtained from the United States Geological Survey (USGS) to improve hydrologic segmentation and subwatershed boundary delineation in the SRW.