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Optimization of conservation practice implementation strategies in the context of stream health

Matthew R. Herman[a], A. Pouyan Nejadhashemi[a,*], Fariborz Daneshvar[a], Dennis M. Ross[b], Sean A. Woznicki[a], Zhen Zhang[c], Abdol-Hossein Esfahanian[b]

[a] Department of Biosystems and Agricultural Engineering, Michigan State University, 225 Farrall Hall, East Lansing, MI 48824, USA
[b] Department of Computer Science and Engineering, Michigan State University, East Lansing, MI 48824, USA
[c] Physical Sciences Division, Department of Statistics, University of Chicago, Chicago, IL 60637, USA

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ABSTRACT

Sustainability and the health of freshwater ecosystems are vital to insure their safe and continued use. This study introduces a new approach to improve stream health to a desirable condition at the lowest cost by optimizing the best management practice (BMP) implementation plan. Several hydrological models including the Soil and Water Assessment Tool (SWAT) and Hydrologic Index Tool were integrated and the results were used to develop a stream health model. SWAT model was calibrated and validated against daily streamflow data from nine US geological gauging stations for a 10-year-period while the stream health model was calibrated and validated against 193 biological monitoring sites operated by the Michigan Department of Natural Resources. The stream health model was guided by a genetic algorithm to design the watershed-scale management strategies that included five BMPs. Out of 182 BMP implementation scenarios, eight unique scenarios resulted in an overall excellent stream health for the Honeyoey Creek-Pine Creek Watershed in Michigan. In addition, no tillage was the most selected BMP in three of the eight implementation scenarios. The BMP implementation costs for these eight scenarios ranged from 4.28 to 6.41 million dollars. Therefore, the integration of genetic algorithm techniques in stream health modeling resulted in a savings of over 2 million dollars. In addition, the implementation of the lowest costing scenario resulted in a 52% improvement and 36% reduction in stream health scores, with respect to stream length, compared to current conditions. The technique introduced here can be successfully adapted in different regions to identify the optimal solution from both environmental and economic points of view.

1. Introduction

With the continued growth of the human population, the need for freshwater use has significantly increased. This increase in freshwater demand is mainly attributed to agricultural production systems, which accounts for nearly 70% of freshwater consumption worldwide (Worldometers, 2014). However, the impacts of anthropogenic activities are not only limited to water quantity but also water quality due to both point and non-point source discharges (Walters et al., 2009; Dos Santos et al., 2011; Giri et al., 2014; Pander and Geist, 2013). For example, water withdrawals and dams alter the flow regime of river systems (International Rivers, 2014), while agricultural production increases nutrient and sediment loads within these systems (USGS, 2013a,b). These combined activities degrade river systems, which in turn impact the humans that use freshwater resources as a source of drinking water or for recreational use. To protect surface water resources, the United States established the Clean Water Act (CWA, 1972), with the goal of restoring the chemical, physical, and biological integrity of the Nation's waterways. In the framework of the CWA, chemical water quality has greatly improved by the implementation of the Total Maximum Daily Load program, administered by the US Environmental Protection Agency (EPA) and point source discharges have largely been eliminated (EPA, 2012). Despite all of these improvements, recent assessment has revealed that degradation of aquatic ecosystems continues and even accelerated since the program was started (EPA, 2011). EPA (2011) report concluded that a central focus on chemical water quality is not enough to achieve healthy

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* Corresponding author.
E-mail address: pouyan@msu.edu (A.P. Nejadhashemi).

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streams due to river system complexity and the effect of compounding stressors (Magbanua, 2012). This shortcoming led to the introduction of bioassessment in river monitoring (Jeong et al., 2012). Bioassessment is an evaluation that uses stream's biological components to evaluate the conditions within the stream (Barbour et al., 1999). The hope is that bioassessment, with both chemical and physical assessments, would provide a more comprehensive view of the stream health, allowing watershed managers to accurately address water quality issues.

Stream health can be defined as the combined quality of chemical, physical, and biological components of a stream (USGS, 2011). The concept of biological integrity for the measure of stream health was introduced by Karr and Dudley (1981), as the ability of an ecosystem to support and maintain a balanced, integrated, adaptive community of diverse organisms in its original stage and before disturbance due to human intervention. Bioassessments, therefore, use indices of biological integrity (biological indicators) to evaluate the livelihood of a system by monitoring the organisms living in a stream (Pander and Geist, 2013). Biological indicators in turn provide a holistic measure that normally takes into account not only the biological characteristics of a system but the physical and chemical conditions as well (Brazner et al., 2007; Pelletier et al., 2012).

Environmental flow is also another element of bioassessment that is critical in monitoring conditions within river systems. Environmental flows describe the regime and quantity of water needed to support both the environment and human needs (King et al., 2009; Poff et al., 2010; Chen and Zhao, 2011). The focus of environmental flows was to initially maintain the minimum levels of water needed to sustain the ecosystem (Alfredsen et al., 2012). However, the scope of environmental flows was further expanded to replicate the natural flow cycles in both timing and volume (King et al., 2009; Alcázar and Palau, 2010; Poff et al., 2010; Chen and Zhao, 2011). The natural flow is defined as the flow rate and characteristics before the introduction of human disturbances or reference condition (Herman and Nejadhashemi, 2015).

In order to maintain environmental flow and minimize the human impacts, stream restoration is necessary in areas with high levels of degradation. In recent years, stream restoration projects have been widely used to maintain and repair ecosystem functions (Pander and Geist, 2013). However, due to financial limitations, it is crucial for watershed managers to identify the best restoration technique for different locations in a watershed. In addition, it is expensive and impractical to perform monitoring for every stream segment to evaluate stream health condition. Finally, it is impractical to examine every possible management scenario to effectively improve overall stream health condition.

By incorporating both biological indicators and environmental flows in stream health assessment, watershed managers are able to identify degraded streams and can work on appropriate implementation plans to restore the ecosystem (Butcher et al., 2003; Neumann et al., 2003; Walters et al., 2009; Pelletier et al., 2012). Use of environmental modeling for bioassessment is an inexpensive and effective way to explore stream health conditions beyond the monitoring sites or examining the impacts of management practices to improve water quality (Arabi et al., 2006; White et al., 2010; Einheuser et al., 2012; Giri et al., 2012; Panagopoulos et al., 2012; Einheuser et al., 2013a,b). However, to the best of our knowledge, no study has been done to optimize best management practices (BMPs) implementation plan in the context of stream health, which is the overall goal of this study. The specific objectives of this study were to: (1) predict stream health conditions beyond the monitoring points based on a biological indicator and (2) develop series of management practice scenarios that maximize stream health conditions while minimizing the associated costs in a watershed.

2. Materials and methods

2.1. Study area

The region used for this study was the Honeyoey Creek-Pine Creek Watershed, located in the central eastern region of the Lower Peninsula of Michigan (Fig. 1). This is a 10-digit hydrologic unit code (HUC 0408020203) watershed and is part of the Pine 8-digit HUC watershed that flows into the Tittabawassee and Saginaw 8-digit HUC watersheds. The final outlet for the region discharges into Lake Huron at the mouth of the Saginaw River. With a total area of 106,131 ha, the region is dominated by agricultural land (52%), followed by forest and wetland (both 20%), and finally pasture (8%). With such a large percentage of agricultural land, water flow throughout this region is in high risk to be altered by water withdrawal for irrigation or degraded by agrochemical nonpoint source pollution.

2.2. Data collection

2.2.1. Physiographic data

Several spatial and temporal dataset were used to characterize the physiographic features of the study area for model developments. These datasets included topography, land use, soil characteristics, climate data, and management practices. The 30 m spatial resolution National Elevation Data set from the US Geological Survey (USGS) was used to represent the topography of the region (NED, 2014). The 30 m spatial resolution 2012 Cropland Data Layer (CDL) from the United States Department of Agriculture-National Agricultural Statistics Service (USDA_NASS) was used to represent the land use for the region (NASS, 2012). Pre-settlement vegetation circa1800 maps were obtained from the Michigan Natural Features Inventory (MNFI) and were used to represent the pre-settlement land use from the mid-1800s (MNFI, 2014). Soil characteristics data was obtained from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database at a scale of 1:250,000 (NRCS, 2014a). Climate data (precipitation and temperature) were obtained from the National Climatic Data Center (NCDC). Within the Saginaw Bay Watershed, 16 precipitation and 13 temperature stations were used to supply daily climatological information. These datasets spanned from 1990 to 2012. Other climate data such as relative humidity, solar radiation, and wind speed were obtained by using the Soil and Water Assessment Tool (SWAT) weather generator (Neitsch et al., 2011). The stream network and subbasins were created from a 1:24,000 National Hydology Dataset plus (NHDPlus) and obtained from the Michigan Institute for Fisheries Research. Each of the 553 subbasins from this dataset contains an individual stream and is considered to be physicochemical, geomorphological, and biological unique (Einheuser et al., 2013a). Management operations, schedules, and crop rotations were modified from SWAT default values, as presented by Love and Nejadhashemi (2011) for the study area.

2.2.2. Biological data

Fish species are commonly used for stream health assessment. This is due to their wide distribution and easy identification as well as their sensitivity to a variety of stressors (Karr, 1981; Mack, 2007; Zhu and Chang, 2008; Navarro-Llácer et al., 2010; Krause et al., 2013). Furthermore, they provide regional evaluation of stream conditions due to their seasonal migrations (Karr, 1981).

For this study, the Index of Biotic Integrity (IBI) was used to evaluate stream health conditions. The IBI, first introduced by Karr (1981), is a multi-metric index that looks at the species diversity, trophic composition, and abundance of the fish community to evaluate stream health. Each metric used in the index is given a score of