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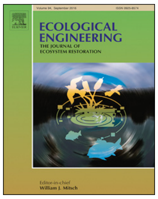

New methodology of evaluation of best management practices performances for an agricultural watershed according to the climate change scenarios: A hybrid use of deterministic and decision support models

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ABSTRACT

Climate change is a primary driver that alters water pollution hotspots in watersheds, which complicates the use of Best management practices (BMPs) for diffuse pollution mitigation strategies. The objective of this study is to evaluate future changes in BMPs on total phosphorus (TP) loads to the river system, depending on climate change. Current weather data were collected from 2000 to 2010 and future weather data from 2040 to 2050 were obtained from regional climate model simulations based on Representative Concentration Pathways (RCP) 2.6, 4.5, and 8.5 scenarios. This study describes various BMP implementation plans at affordable cost that are adapted to different weather conditions, current (for 2000–2010) and future climate scenarios (for 2040–2050). The Soil and Water Assessment Tool (SWAT), i.e., one of the deterministic models for watershed management, was used to estimate total phosphorus (TP) removal efficiency of various types of BMP at two crop fields (rice paddy and soybean fields) in the Yeongsan River (YR) watershed of Korea. The Non-dominated Sorting Genetic Algorithm II (NSGA-II), i.e., one of the artificial intelligence (AI) models for decision support framework, was applied to obtain allow for trade-off analysis between two conflict objectives, the maximum TP load reduction against implementation costs. The SWAT simulation results showed that the model performance based on the Nash-Sutcliffe efficiency and percent bias was acceptable for simulating three parameters; daily flow discharge, monthly sediment loads, and TP loads in the river. As a result, monthly sediment loads and TP loads increase remarkably under all future climate change scenarios except for July, when a comparable amount of precipitation is recorded during the present and future conditions. New implementation of BMPs, therefore, will be required for future climate change scenarios to achieve 50% TP load reduction in the given watershed condition. Interestingly, parallel terraces which showed good efficiency in reducing TP loads at both fields under the current weather condition cannot be effective any more under the worst-case weather scenario in the future climate. In such a case, detention ponds can be proposed as BMP alternative to parallel terraces. Overall, this study not only demonstrates that watershed management plans using BMPs should be adjusted according to climate change scenarios, but also that the hybrid use of SWAT model and AI can help in refining existing and future BMPs at affordable cost.

1. Introduction

Climate change, which is accompanied by an increase in atmospheric concentrations of greenhouse gases such as carbon dioxide and ozone (i.e., global warming), weakens security of global water resources (Vörösmarty et al., 2000). The (global) hydrologic cycle intensifies with strong climate change, which redistributed water on the planet beyond expectations of climate models based on historical weather records (Allen and Ingram, 2002). In fact, projections of different levels of future climate scenarios available from the Intergovernmental Panel on Climate Change (IPCC) to the climate models was found to show substantial increases in global-mean evaporation

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and precipitation on average (Labat et al., 2004; Li et al., 2013). This clearly implies that significant changes of hydrologic regimes (e.g., more rapid runoff and flooding), contaminant transport processes (e.g., increased sediment and chemical fluxes), and ecosystem functions (e.g., less abundant species and diversity) in water resources will occur under future climate conditions (O'neil et al., 2012; Peperzak, 2003). Therefore, new mitigation strategies are needed at all sectors relying heavily on water resources, even though episodes on water crisis (e.g., water shortage, contamination, and water-related disasters) differ considerably across the regions, in addition to the climate models and future scenarios (Iglesias et al., 2007; Werritty, 2002).

Best management practices (BMPs) are commonly known as an alternative management strategy to reduce nonpoint source (NPS) pollutants by controlling runoff, sediment, and nutrient losses from agricultural areas (Kaini et al., 2008; Lam et al., 2011). BMPs can be classified into structural and non-structural management practices. Structural BMPs such as pond, terraces, wetland, and filter strip are commonly applied to natural systems (Kaini et al., 2008). Non-structural BMPs, including tillage practices and control fertilizer, are institutional and educational practices designed to minimize pollutants or amount of stormwater runoff (Lam et al., 2011). The effectiveness of BMPs for controlling NPS varies depending not only on the type of crops, but also on geological and hydrological characteristics of watersheds (Maringanti et al., 2009). Thus, the performance of BMPs should be sensitive to climate change. A modeling study by Woznicki and Pouyan Nejadhashemi (2014) revealed that the performance of BMPs varied both seasonally and spatially by differing climate scenarios. Although they may not be suitable under future climate and hydrological conditions (Woznicki and Nejadhashemi, 2012), many BMPs implementation strategies recently developed have not taken climate change into account (Arabi et al., 2006; Kaini et al., 2012; Maringanti et al., 2009; Srivastava et al., 2002).

This study aims to assess how the relative effectiveness of agricultural BMPs changes with changing climates, hypothesizing that an optimal BMP in the current climate may not be optimal in warmer future climates. To explore the impacts of climate change on the performance of BMPs, we used the SWAT model. The SWAT model has been widely used for assessing the impacts of climate change on surface runoff and NPS (Githui et al., 2009; Gosain et al., 2006; Hanratty and Stefan, 1998; Jha et al., 2004). The effectiveness of implementation of BMPs removing non-point nutrient inputs from agricultural areas has been explored with the SWAT model (Bracmort et al., 2006; Gitau et al., 2008; Lee et al., 2010). However, the SWAT has been rarely used to compare the performance of various BMPs under different climates. In this study, the SWAT model was run under three different climate change scenarios (RCP 2.6, 4.5, 8.5).

Coupled with the SWAT, the Multi Objective Decision Support System (MODSS) was used to select optimal BMPs that represent the best compromise between load reduction and implementation cost (Bekele and Nicklow, 2005; Maringanti et al., 2011). We applied the SWAT and the MODSS to the Yeongsan River (YR) watershed, Korea. Dominated by agricultural areas (33%), the YS River watershed has caused eutrophication and serious algal blooms in the river (Cha et al., 2009; Cho et al., 2009). Based on the case study, optimal BMPs with respect to both load reduction and cost were selected and allocated across the watershed, and the effects of climate conditions on the effectiveness of BMPs implementation were analyzed.

2. Materials and methods

2.1. Site description

The study site is located in the upper reaches of the YR watershed in South Korea (Fig. 1). The watershed area is approximately 724 km^2 and is divided into nine sub-watersheds. The land use within the watershed primarily consists of forests (51%) and rice paddies (24%). Other land use types include soybean fields (10%), urban areas (9%), and hayfields (4%). Nonpoint source pollution, in particular from agricultural activity, has been the major source that caused the deterioration of the water quality of the Yeongsan River (Kang et al., 2010, 2009; Ki et al., 2007). The whole process from preparing input files to develop SWAT model to comparing optimal BMP implementation strategies under different climate conditions is presented in Fig. 2.

2.2. Model development

2.2.1. Description of SWAT model

The SWAT, developed by the United States Department of Agriculture, has been widely used to evaluate the impacts of agriculture activity on water quality in a watershed on a daily basis. Therefore, SWAT model can compare the performance of differing BMPs under various climate conditions at the watershed-scale (Arnold et al., 1998). SWAT model is a physical-based and continuous-time model and appropriate to simulate over long periods of stream flow, and loadings of nutrients and pesticide. The SWAT model for the YR watershed simulated daily flow discharge, monthly sediment loads and total phosphorus (TP) loads at the Mareuk (MR) station located at upstream of YS River. A watershed in a SWAT model is divided into a number of subbasins which are subdivided into hydrologic response units (HRUs), each of which is comprised of homogeneous land use, slope, and soil type (Gitau et al., 2004).

2.2.2. Data description

Topographical, land use, soil, and point source pollution data were obtained from the online water management information system (WAMIS) (http://www.wamis.go.kr). The topographical data were used to generate a stream network, a basin, and sub-basins. The land use data, obtained from the WAMIS, were used to generate 16 different land use types, including forest, agriculture, and urban areas. The soil within the watershed was classified into 164 different types. The point sources of pollution included discharge from two sewage treatment plants located in the basin. Meteorological data were acquired from the Korea Meteorological Administration (KMA) web site (http://www.kma.go.kr). The agriculture activity database was acquired from the Korea Rural Development Administration (http://www.rda.go.kr). The database included the timing of tillage operation, fertilizer application, planting/beginning of growing season, harvest and kill operation, the quantity of fertilizer applied and the method of tillage. Water quality data, acquired from the Korea water information system web site (http://water.nier.go.kr), included daily flow discharge, monthly sediment concentration, and monthly TP concentration sampled at MR station from year 2000–2010.

2.2.3. Sensitivity analysis, model calibration and validation

A sensitivity analysis on model parameters was performed based on the Latin Hypercube One-factor-At a Time (LH-OAT), a combination of the Latin hypercube (LH) sampling as an initial point and OAT design (Holvoet et al., 2005). The LH simulation, as an alternative to Monte-Carlo sampling, simultaneously selects random values over the parameter space (McKay et al., 1979). Through the sensitivity analysis significant parameters for calibrating the SWAT model were determined.

The simulation period was 11 years from 2000 to 2010, which was further divided into 3 subperiods: spin-up period (2000–2002), calibration period (2003–2006), and validation period (2007–2010). The parameters selected from the sensitivity analysis were used for calibration. The Nash-Sutcliffe efficiency coefficient (E_{NS}) (Eq. (1)) (Krause et al., 2005), and the percent bias (PBIAS) (Eq. (2)) were used for model evaluation.