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A Review and Discussion on Modeling and Assessing Agricultural Best Management Practices under Global Climate Change

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Abstract

Understanding the impacts of global climate change on the spatiotemporal pattern of hydrologic cycle and water resources is of major importance in highly developed watersheds all over the world. These impacts are strongly dependent on related changes in intensity and frequency of extreme climate events. Implementation of Best Management Practices (BMPs) and policy approaches at watershed and regional scales is essential for mitigating their negative impacts on soil and water conservation, and sustainable economic development. However, the uncertainty of BMP effectiveness including increasing variability of future water supply and changing magnitudes of nonpoint source pollution has to be accounted for in watershed planning and management. This paper provides a review and discussion on the impacts of global climate change on BMP's hydrologic performance, the current progress on hydrologic assessment of BMPs, as well as the existing problems and countermeasures. Research challenges and opportunities in the field of hydrologic assessment of BMPs under global climate change are also discussed in this paper.

Keywords: agricultural BMPs; hydrologic modeling; non-point source pollution; global climate change

1. Introduction

Studies in recent decades have indicated that global climate has changed significantly in the past 10,000 years (IPCC, 2012). Consequently, strategies and policies on adaptation to future climatic change have been more emphasized in these scientific studies. In many areas, degradation of water quality in rivers and lakes is mainly caused by nonpoint source (NPS) pollution associated with intensive agriculture and rapid urbanization (Li et al., 2007). Precipitation and temperature are the two main climate processes governing NPS pollution, both controlling the rate of runoff and the pollutant loading as a result of water balance and ecosystem changes. Runoff acts as a carrier for sediments, nutrients and other pollutants from various sources, and finally deposits them into receiving water bodies, such as rivers, wetlands, lakes, and groundwater. The demand for food supply and economic development causes conversion of natural vegetation into crops or urban land cover, leading to more surface runoff and nutrients loss than undisturbed soils. This situation is becoming more complicated when considering the effects of global climate change (GCC) associated with increasing intensity and frequency of extreme storm events. Storms with high intensity cause more severe erosion, nutrient loss and leaching than those under normal condition. Long term effects of GCC are also of great concern because it changes other hydrologic processes, such as evapotranspiration, soil moisture, and plant growth.

Considering the impact of GCC on NPS pollution, effective management practices towards reducing NPS pollution should aim at reducing contamination during extreme events, and emphasize the practices of intercepting and filtering pollutants on their pathways towards receiving water body. Best Management Practices (BMPs) are widely recognized as effective measures in reducing NPS pollution in agricultural watersheds (Beegle et al., 2000). These practices, including structural and non-structural, are developed to achieve a sustainable balance between water quality protection and economic development within a watershed under natural and economic limitations. Various conservation programs have been designed to implement BMPs in agriculture such as filter strip, riparian buffer, conservation tillage, and nutrient management. The study of BMPs has a long history, and their environmental benefits have been measured at different scales. In particular, progress in integrated evaluation of agricultural BMPs has been made in recent years, e.g., the USDA Conservation Effects Assessment Program (CEAP), and the Watershed Evaluation of BMPs (WEBs) program in Canada (Yang et al. 2007).

The environmental effects of BMPs can be evaluated through experimental monitoring and model simulation. The approach of experimental monitoring is time and cost consuming. Additionally, BMP effects are site-specific in that the effective BMPs obtained from one experimental site may not be applicable to other watersheds. Complementary to experimental monitoring, model simulation based on available data and knowledge is more practical because it integrates different watershed processes in one system, and can provide spatially explicit and detailed outputs. Numerous watershed modeling studies have been conducted worldwide in evaluating the effect of various BMPs on NPS pollution control, water resources development, and ecosystem sustainability, such as Zhang and Zhang (2011), Ackerman and Stein (2008), and Bracmort et al. (2006). Most of these evaluations are based on historical and existing climate and land use conditions. On the other hand, the impacts of GCC on BMP performance and cost-effectiveness have attracted increasing attention in BMP studies, e.g. Arabi et al., 2006. Becker and Grünewald (2003) pointed out that global warming should be accounted for by considering BMP effects under warmer climate conditions in hydrologic model predictions. BMP evaluation based on historical records alone might be inadequate for assessing their future impact, and therefore, a safety factor needs to be added to incorporate hydrologic modeling uncertainties as a result of climatic change, e.g. the studies addressed in Wilby et al. (2006), Rahman et al. (2012), and Jha and Gassman (2013). Hydrologic predictions based upon historical climate record and existing land management conditions could result in a biased estimation of future BMP performance. However, no significant achievements have been made so far in improving the assessment of BMP performance under GCC.

The objective of this paper is to discuss the potential impact of GCC on hydrologic performance of BMPs, to summarize the current progress in addressing these problems, and to highlight the scientific challenges in studying the impacts of GCC on BMP hydrologic performance for adaptive water quality management and sustainable agricultural development. Although numerous studies on BMP effects and climate change impacts on hydrology have been undertaken in recent decades, the scientific development on integrating climate change impacts and BMP assessment is very limited. This paper serves to identify the knowledge gap and propose future research directions.

2. Impact of GCC on Water Cycle and BMP Performance

GCC is expected to have adverse impacts on our water resources and ecosystems at different scales. Previous studies have demonstrated that global warming may increase water scarcity and threaten water resources availability, and is anticipated to cause various environmental problems in the future (Piao et al., 2010). GCC would result in changes of various variables, such as precipitation and runoff pattern, sea level, land use, and biodiversity. Warmer temperature will alter hydrologic cycle and water balance in terms of magnitude, timing, intensity, and frequency of precipitation, evapotranspiration, flood and drought. Higher temperature will lead to an increase of potential evapotranspiration, and consequently alter infiltration, percolation, soil moisture, as well as snowfall and snowmelt. The combined effect of shorter duration, more intense rainfall, increased evapotranspiration, and increased water use will accelerate depletion of future groundwater storage and low flow in rivers (Earman & Dettinger, 2011).

GCC is one of the major factors that cause the change of flood magnitude and frequency (WHO, 2002). With respect to severe flooding, the large amount of precipitation and the higher frequency of intense rainfall events are the two major environmental drivers and have important impacts on flooding characteristics and damage potentials. According to the UNGC-PI White Paper (2009), GCC will affect water quantity by (a) increasing water scarcity as a result of changed precipitation patterns and intensity; (b) decreasing the capacity of natural water storage as a result of increased glacier and snowcap melting, and subsequently affecting the long-term availability of water resources; (c) increasing the vulnerability of ecosystems which will in turn lower the capacity of natural earth systems to prevent flooding and protect water quality; (d) affecting the water supply infrastructure in terms of their reliability and capacity because of the extreme weather, flooding, drought, and sea level rise, and (e) altering natural water uses such as water transfer into inland dry areas. The impacts of GCC on water quality include (a) increasing the magnitude and frequency of extreme events, and consequently increasing the rate of erosion particulate pollutants from uplands and channels; (b) degrading surface and groundwater resources in coastal areas as a result of sea level rise and saltwater intrusion; (c) increasing temperature in water bodies, and contaminating water supply as a result of eutrophication and bacterial pollution; and (d) contributing to risks associated with water and environmental health. All these alterations will significantly affect the performance of BMPs in the processes of runoff, groundwater recharge, sediment, and nutrient losses at local and regional scales. Specifically, GCC may result in following three changes on the hydrologic performance of BMPs.

2.1 BMP Performance May Change in Different Magnitudes with Respect to Pollutant Composition

Change in magnitude refers to the BMP reduction rate on peak pollutant loading under a climate change scenario in comparison to the BMP reduction rate under existing climate conditions. Under a climate change scenario, precipitation and temperature may undergo significant changes in magnitude, trend, frequency, and return period. As a result, hydrologic regimes may differ significantly from the existing condition, and BMP effects would be considerably different from those under existing condition. Some BMPs may have a much higher reduction rate, and some may have much less reduction rate in terms of magnitude and total amount. The change of hydrologic regime may also result in a change of pollutant composition in storm water. For example, extreme flooding usually comes along with severe soil erosion and sediment yield at both field and watershed scale, and consequently the fraction of particulate (sediment-bound) contaminants in the total loading would increase. In areas where dissolved pollutants, e.g. dissolved phosphorous and dissolved nitrogen, are dominant, BMPs are typically designed to remove these dissolved pollutants from their sources (Rao et al., 2009). When high sediment concentration is present in channels, the objective of BMPs shall focus more on reducing sediment-bound pollutants, e.g. particulate phosphorous and particulate nitrogen, from their sources and transport pathways.

Typically multiple BMPs are implemented at multiple sites within a watershed for NPS pollution control. For example, crop management, fertilizer management, tillage management, filter strips, retention ponds, and riparian buffers may be jointed implemented in a watershed by different producers. Some of them are more cost-effective than others in reducing NPS pollution under existing climate condition. However, the relative importance of these BMPs in terms of cost-effectiveness may change under climate change condition. For instance, the riparian buffer BMP could be more cost effective in reducing NPS pollution under existing condition, but becomes less cost-effective for extreme events because of increased concentrated flow that bypasses riparian buffers without flow and sediment attenuation (Liu et al., 2007). This phenomenon should be taken into consideration when evaluating BMP performance for a climate change scenario.

2.2 Practices May be No Longer Functional

BMPs are typically designed to improve water quality by controlling NPS pollution from land surface into streams and rivers through runoff and erosion, and into soil profile and groundwater through infiltration and leaching. However, in some areas of the world such as the North China Plain, affected by GCC and intensive human activities, streams are dried up frequently at both local and regional scale due to storage losses in upstream areas (Li et al., 2007). This would make BMPs, such as crop management, tillage management, and fertilizer management, no longer functional in improving water quality in mainstreams, because whether or not the BMP is implemented, there would be no water in mainstreams. Similarly, extreme flooding conditions may override functionalities of some structural BMPs, such as terrace and filter strip (Strauch et al., 2013). Because these BMPs are designed for normal climate conditions, severe flooding may damage these structures and make these BMPs ineffective in minimizing erosion and NPS pollution from upland fields.

2.3 Practices May Shift from Sink to Source of Pollutants

BMPs are expected to be effective in preventing or minimizing hydrologic connectivity between pollutant source area and the receiving water body such as lakes and stream channels. For example, riparian buffers are designed to retain sediment and other pollutants before they reach lakes or streams, and retention ponds are designed to collect storm water runoff and accelerate biological breakdown of contaminants. These BMPs are effective under normal climate conditions and serve as sinks of contaminants generated from the BMP contributing area. This situation may change under the condition of extreme events. Severe flooding may destroy the structure, and the accumulated pollutants may flush out of the BMP area causing serious pollution in receiving water bodies (McDowell and Nash, 2012). As extreme events would become more frequent under climate change condition, some BMPs that are designed at a specific location and at a certain capacity under normal climate condition may negatively impact the water quality in streams and lakes, and these ‘best’ management BMPs may shift to ‘bad’ management practices if they are not properly designed and maintained.

3. Hydrologic Assessment of BMPs under GCC

Figure 1 shows typical assessment steps of climate change impacts on hydrologic performance of BMPs at various scales. Global Climate Models (GCMs) are used to predict future potential climate changes caused by changes of aerosols, greenhouse gases concentrations, land cover, population, economic growth, and other factors. Based on estimates of these factors, GCM models simulate the circulation patterns of atmosphere and their variability over the coming centuries. Statistical Downscaling Models (SDMs) are used to refine GCM climate data at finer spatial scale. Dynamic Downscaling Models (DDMs) are fine-scale climate models nested inside the coarse-scale GCMs. Both models provide outputs on climate change at a local scale (Simonovic and Li, 2003). Hydrologic models at watershed scale are conceptual and simplified representations of the natural hydrologic cycle, and are typically used for understanding hydrologic processes and for hydrologic predictions. Modern watershed hydrologic and management models, such as the Soil and Water Assessment Tool (SWAT), have incorporated management practices in the modeling system and allow the evaluation of BMPs at subbasin and watershed scales (Arnold et al., 1998). Several commonly used hydrologic models for assessing agricultural BMPs are listed in Table 1. BMP hydrologic models are specifically designed for planning, evaluation, and implementation of BMPs at site, field, and farm scales that are compatible with the assessment result of hydrologic models at watershed scale. These models, e.g. Agricultural Policy Environmental Extender (APEX), evaluate BMP performance at a finer scale and their outputs can be used as inputs to watershed models to improve their modeling results and reduce output uncertainty (Williams et al., 2000).

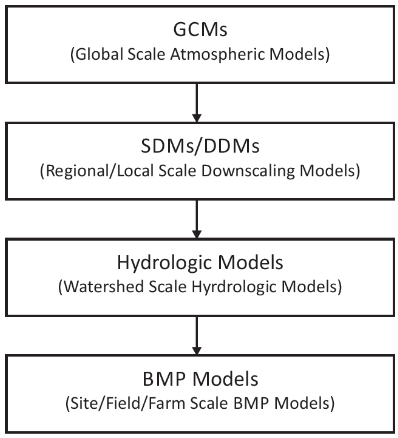

Figure 1. Steps in assessing climate change impacts on hydrologic performance of BMPs at site/field/farm/watershed scales

Table 1. Several commonly used hydrologic models for agricultural BMPs assessment

Model	BMPs	Remarks
Agricultural Non-Point Source Pollution Model (USDA, 1998)	Agricultural practices, ponds, grassed waterways, tile drainage, filter strips, riparian buffers	Distributed parameter, event-based, water quantity and quality simulation model
Areal Non-point Source Watershed Environment Response Simulation (Bouraoui et al., 2002)	Agricultural management, ponds, grassed waterways, tile drainage	Event-based or continuous, lumped parameter runoff and sediment yield simulation model
Chemicals, Runoff, and Erosion from Agricultural Management Systems (USDA, 1980)	Agricultural management, grazing, fertilization, filter strips	Process-oriented, lumped parameter, agricultural runoff and water quality model
Hydrologic Simulation Package-Fortran (Bicknell et al., 1993)	Nutriment and pesticide management, ponds, urbanisation	Continuous, event or steady-state simulator of hydrologic and water quality processes
Soil Water Assessment Tool (Arnold et al., 1998)	Agricultural practices, ponds, irrigation, tile drains, grazing	Distributed, conceptual, continuous simulation model
Storm Water Management Model (Huber, 1995)	Detention basins, street cleaning	Process-oriented, semi-distributed, continuous storm flow model
Agricultural Policy Environmental Extender (Williams et al., 2000)	Land management practices	Farm/small watershed scale model for evaluation of sediment and nutrient losses

Watershed models can be classified into spatially lumped/semi-lumped and fully distributed models. Spatially semi-lumped models, such as the SWAT, aggregate areas with similar topographic, soil, and land use features within a subbasin into one computational unit, and assume no hydrologic interactions between the units. These models have advantages in assessing BMP performance at large scales, but have limitations in evaluating individual BMPs, particularly the structural BMPs, for land management at a small watershed scale (Ullrich and Volk, 2009; Bracmort et al., 2006). Fully distributed models are typically raster-based, e.g. the Agricultural Non-Point Source Pollution Model (AGNPS), and can be used for evaluating BMP performance at fine scales. However, these models need more computer memory and are time consuming when modeling a larger scale watershed with a small cell size. With respect to time scale, watershed models can be classified into temporally lumped and explicit ones. Temporally lumped models, such as the SWAT, typically run at a daily time step, and produce an average estimate for long term assessment. These models simplify watershed hydrologic processes with a relatively coarse temporal resolution, and therefore have limitations in simulating dynamics of runoff and water quality processes during an extreme flood event. Temporally explicit watershed models use short time steps in hourly and sub-hourly, or even finer resolution, such as the Hydrologic Simulation Package-Fortran (HSPF), and are able to simulate dynamics of hydrologic processes in a great detail during a single flood event. However, these models are typically less efficient in spatial representation of a watershed or lack a physical basis for reproducing runoff and water quality processes (Borah and Bera, 2003). Other physically-based models, such as the Systeme Hydrologique Europeen (MIKE-SHE) (Abbott et al., 1986), may address these problems to certain extent, but are highly data intensive and not specifically designed for BMP assessment. This makes the selection of watershed models more difficult for evaluating BMP performance under GCC.

Modeling and assessing the impact of GCC on hydrologic processes have attracted an increasing amount of research efforts in recent years. Simonovic and Li (2003) presented a framework for modeling and assessing the impact of climate change and variation on the model performance for a flood protection system in the Red River basin, Manitoba, Canada. Within the modeling framework, GCMs are incorporated in the system allowing for the evaluation of different climate change scenarios on flooding characteristics. An approach of dynamic modeling and simulation was used to assess flood peaks and volumes, flood control structure capacities, and bank failure discharges at various locations in the basin. Applying the SWAT model in the Fox River watershed in Illinois, USA, Bekele and Knapp (2010) assessed the potential impacts of climate change on surface water and low flow through analysis of model sensitivity to a range of climate change scenarios. The evaluation results showed that increasing precipitation would significantly change stream flow patterns in late summer and fall period, and increasing temperature would greatly affect snowmelt and winter flows. Similar results were also found by Rahman et al. (2012) through implementing the SWAT in a Southern Ontario watershed, Canada for a future climate change scenario. They predicted increases of up to 23.1%, 28.1%, 39.8%, and 19.6%, respectively, of evapotranspiration, groundwater recharge, stream flow, and total phosphorous under the projected future climate change scenario. These modeling studies focused on the impacts of climate change on general hydrologic processes in various watersheds, but did not account for the impacts of different landscape BMPs under GCC.

Van Liew et al. (2012) applied the SWAT model to examine the impacts of potential climate change scenarios on stream flow, water quality, and BMP performances for two watersheds in Nebraska, USA. In addition to the predicted considerable increases of stream flow, sediment, and nutrient responses, a targeting approach was employed to compare the impact of five BMPs on stream flow and water quality in the study area. Simulation results indicated that of the five BMPs tested in this investigation, the conversion of cropland to switchgrass and the conversion of cropland to pasture were the most effective BMPs while no-till was the least effective. Similar results were also reported by Woznicki et al. (2011) who employed the SWAT to assess BMP impacts for two watersheds in Nebraska and Kansas, USA, under future climate change scenarios. Findings of this study indicated that under future climate change scenarios the switchgrass and pasture treatments could produce significant sediment and nutrient load reductions compared to simulation results under current baseline condition. Specifically, using the SWAT, Woznicki and Nejadhashemi (2012) analyzed the sensitivity of eight agricultural BMPs with respect to flow, sediment, total nitrogen, and total phosphorous under various climate change scenarios for the two watersheds in Nebraska and Kansas, USA. For each climate scenario, the sensitivities were analyzed on annual and monthly basis by altering model parameters associated with BMP implementations. Results indicated that the practices of terraces, native grass, and contour farming were the most effective BMPs in reducing NPS pollution of the watersheds in future climate scenarios, whereas other BMPs including no-tillage and porous gully plugs were less sensitive from the sensitivity analysis results. The study also found that BMP sensitivities varied significantly on a seasonal basis for all climate change scenarios based on the monthly sensitivity analysis results.

The aforementioned studies all used the SWAT as a modeling tool and assumed the model is capable of predicting the responses of flow, sediment, and nutrient cycle for future climate change scenarios. Though the future projections of flooding and drought are much severe, the BMP's relative performance level remained almost the same, and no studies provided an estimate of ineffective or negative BMP impacts under GCC as discussed in Section 2. It is expected that significant potential uncertainties on the modeling estimates could exist in assessing BMP impacts for future climate change scenarios. As BMP's performance is very sensitive to GCC, cautions should be taken in the decision-making of BMP planning and management (Woznicki and Nejadhashemi, 2012).

4. Research Challenges and Opportunities

Based on above analysis, efforts should be made to incorporate GCC into the assessment and implementation of agricultural BMPs at different spatial scales. In addition to social, political, economic, and environmental implications, there exist a range of scientific challenges, such as developing reliable future climate scenarios, adapting watershed models for BMP assessment under extreme events, developing techniques for multi-scale and multi-objective BMP assessment, and limiting overall uncertainties in the BMP assessment under GCC.

4.1 Development of Reliable Future Climate Scenarios for Hydrologic Analysis

Future climate scenarios and climate simulation rely on proper identification of causes, GCM projections, and downscaling methods. Despite debates and discussions on the causes of climate change, evidences have shown that GCC has been of increasing significance during the last century by human activities through increases of trace gases in the atmosphere (IPCC, 2007). However, critical questions exist on their influencing extent and corresponding adaptation measures under GCC condition. These questions are difficult to answer using existing models when various uncertainties exist (Sivakumar and Sharma, 2009). GCM projections are used to characterize the changing climate, but uncertainties are associated with model predictions in the change of atmospheric greenhouse gas concentrations (IPCC, 2007). As a result, different GCMs may produce different climate change patterns for the same emissions scenario. For example, uncertainty in precipitation predictions affects modeling performance because precipitation is the most important influencing factor on hydrologic processes (Teutschbein & Seibert, 2010). With improved scientific understanding of the climate systems and the availability of accurate observations of physical parameters, these problems could be further addressed in the climate change studies.

The knowledge of downscaling has been improved significantly in recent decades (Maraun et al., 2010; Winkler et al., 2011). However, GCMs produce climate change scenarios at a much larger spatial scale than the ones used for watershed scale hydrologic and BMP studies. Therefore, downscaling techniques, such as SDMs and DDMs (Figure 1), are developed to transform GCM outputs to watershed scales. These downscaling approaches are typically conducted for daily or monthly transformation of precipitation and temperate, which are difficult to be used directly for generating extreme events. Studies have shown that these approaches can produce downscaled simulations with an acceptable degree, while the quality of prediction relies strongly on the accuracy of GCM results and transformation functions (Sivakumar and Sharma, 2009). Considering the system's nonlinear and chaotic dynamic nature, new downscaling approaches are needed to overcome these drawbacks and provide more reliable climate scenarios for watershed hydrologic and BMP studies.

4.2 Model Adaptation Considering the Effects of Extreme Event on BMP Performances

The modeling approach can not only simulate the responses of BMPs in hydrologic system, but also provide spatial variations of the responses which are very important for assessing BMP performance and for spatial watershed management. While we are facing an unpredictable future, it would be important to develop adaptation strategies based on lessons from the existing practices. Over the last two decades, significant developments have been made in advancing hydrologic models for scientific research and practical applications through the use of remote sensing, geographical information system, database management, 3D visualization, auto-calibration and optimization techniques, and advanced computer hardware and software (Yang et al., 2010). Current commonly used BMP assessment models, such the SWAT, typically provide an average estimate, and are used for long-term evaluation of BMP effects under normal climate conditions (Douglas-Mankin et al., 2010). One problem of these simulation models is their performance on reproducing and predicting extreme hydrologic events such as severe flooding and drought (Kahl et al., 2010). Such extreme hydrologic events are expected to occur with higher frequencies and greater magnitudes in future climate scenarios. They may alter the function and efficiency of BMPs, such as riparian buffers and holding ponds, particularly for extreme events beyond current design standards of BMPs. Therefore, adaptation of available models or development of new models accounting for the impacts of extreme events on BMP performance is necessary.

Hydrologic models with relatively coarse spatial and temporal resolutions, such as the Hydrologiska Byrans Vattenbalansavdelning (HBV) model (Bergstrom, 1995), are easy to apply due to their low data requirement and general representation of hydrologic processes. These models are suitable for general watershed simulation, but are limited in BMP assessment which needs much detailed process representations. High spatial resolution models can capture details of hydrologic processes, identify BMP effects at site scale, and help in the ultimate placement of BMPs for spatial watershed management. Simulation of BMP effects with small time steps is also essential because NPS pollution is severe during intense flooding events. However, these types of models also suffer many limitations, such as data requirement, time consuming, computational methods, and the assessment of model uncertainties. For better understanding BMP effects on water quality under GCC, models that are able to simulate spatially detailed hydrologic processes in terms of runoff, erosion, and nutrient cycle with small time steps are essential.

4.3 Assessment of BMP Impacts at Multi-Scales

Scale issues in terms of spatial and temporal resolution have been an important topic in hydrologic modeling. Scale issues will become more prominent for BMP assessment under climate change. Observations for BMPs are typically conducted at site, plot or field scale, where the topographic, soil, weather, and land management conditions can be considered relatively uniform. At the watershed scale, BMP evaluation aims to assess the cumulative effects of multiple BMPs implemented at different places and times. Because of the high heterogeneity of watershed conditions, considerable uncertainties could be introduced to the observations and evaluations, and the timing, intensity, and spatial distribution of climatic variables would become key determinants of BMP effects on water quality (Li et al., 2011). Additionally, in-stream processes or improper maintenance of stream management practices may result in a much lower BMP effectiveness at a watershed scale than that observed at site, plot, and field scale. Because of the variations from other locations in the watershed, significant positive changes may not be observed at the watershed outlet after BMPs implementation at specific locations within the watershed. At the regional scale, BMP assessment will focus more on the general trends of BMP impacts on regional environment, answer the questions such as which areas are more critical in reducing pollutant loading, and which types of BMPs are more effective in different areas of the region, but will not focus on the evaluation of individual BMPs at a hillslope scale (Arnold et al., 2010).

Models at the field scale are typically used for BMPs design and management, such as crop management, irrigation, and wetland restoration. At a watershed scale, models are used for integrated BMP assessment, such as flood protection, erosion control, water quality evaluation, and BMPs cost-effectiveness optimization. The performance of a hydrologic model is greatly influenced by data variations and processing at spatial and temporal scales (Singh and Woolhiser, 2002). Many hydrologic models, such as the SWAT, employ mathematical equations based on mass and energy balance. These equations need to be up-scaled to develop compatibility between the observation data and the governing equations. As a result, characterization at a fine scale may be lost due to the effect of averaging and aggregation in both time and space. Model parameters are typically determined based on maps of topography, soil, land use, and other geospatial features using GIS and remote sensing techniques. The averaged parameter estimates may not represent accurately the actual landscape characteristics. In addition, different spatial and time scales also cause difficulties in interpolating the climate change estimates when evaluating BMP performances in future climate scenarios. It is desirable to adapt or develop models with a flexible and robust structure that are able to characterize processes at different scales with an acceptable degree of certainty for BMPs assessment under climate change.

4.4 Assessment of BMP Impacts with Multi-Objectives

BMPs are typically designed for reducing sediment and nutrient export to the receiving water bodies, protecting soil quality, and meanwhile increasing or maintaining agricultural production. Accordingly, hydrologic models are developed with the objective to improve water quality in water bodies when assessing the effectiveness of BMPs at different temporal and spatial scales. However, in semi-arid areas like the North China Plain, streams are frequently dried-up in rural areas because of intensive agricultural development and water use in upstream areas (Li et al., 2007). The use of hydrologic models in these areas is limited because almost no water in local streams all year round under normal conditions. This situation may become more severe under GCC. BMPs could be designed in these areas to reduce ineffective evapotranspiration, increase irrigation efficiency, improve soil fertility, and reduce the risk of soil salinity. Another example is in the arid inland areas, such as the Tarim River Basin in Northwest China where stream water coming from snow and glacier melt in upstream mountains is a source of irrigation rather than runoff contribution from agricultural lands (Fan et al., 2013). Therefore, to maintain and improve the fragile ecosystem in oasis areas under GCC is an important objective that BMPs need to address in these areas. In view of these challenges, models that serve multi-objectives for BMP assessment under different climate and geographical conditions need to be developed.

In recent years, increasing studies have been conducted to identify optimal placement of agricultural BMPs to achieve multi-objectives in minimizing economic costs and maximizing water quality benefits. These studies integrate economic and hydrologic models to examine cost effectiveness of BMPs based on a multi-objective function that optimizes both economic and water quality benefits within a watershed. Many optimization algorithms have been developed at different scales for cost effective placement of BMPs to reduce pollutant loadings in streams (e.g. Rodríguez et al., 2011; Maringanti et al., 2011). These complex optimization searches have shown significant advantages compared to conventional targeting and random placement techniques. To address the aforementioned multiple objective problems, methodologies for optimal BMP placement can be further developed to incorporate a suite of factors such as water quantity and water quality with respect to different pollutants. Given the likelihood of projected increases in runoff and pollutant loadings under the condition of GCC, a challenge to modellers would be how to effectively employ these new methodologies for spatial BMP placement and management (Van Liew et al., 2012).

5. Estimation of Uncertainties Associated with BMP Assessment

Evaluation of BMP performance under climate change is closely related to climate pattern and future probability of extreme events influenced by uncertainties of future climate change. Typically sources of uncertainties in the hydrologic modeling and assessment of BMPs include: (a) uncertainties in the geospatial data which are used for model setup including DEM, soil, land use, watershed boundary, and stream networks; (b) uncertainties in the climate and hydrologic data which are used for model input and calibration; (c) uncertainties of land management data which are essential inputs for BMP assessment; (d) uncertainties in specification of hydrologic model parameters and BMP parameters, and (e) others such as lag time uncertainties between BMP placement and observed water quality benefits, and uncertainties in model representation of influencing factors on pollutant load delivery to receiving waters. As pollutant loads are highly sensitive to the variability of climate data (Woznicki and Nejadhashemi, 2012), uncertainty in climate inputs is therefore an important factor to limit the credibility of BMP assessment results under GCC. These uncertainties may arise from the identification of key factors that cause future climate change, the development of future emissions scenarios, the credibility of future climate projections at different scales, the development of downscaling methods, and finally the hydrologic analysis and predictions at different spatial and temporal scales (Sivakumar and Sharma, 2009). Uncertainties also exist when disaggregating downscaled daily precipitation data into a finer time step for use in modeling extreme events. The hydrologic models and BMP assessment models have common but also different uncertainties in terms of model conceptualization, structure, parameters, calibration procedures, and result interpretations. A detailed discussion about uncertainties in the hydrologic modeling at watershed scale can be found in Beven (2002) and other literature.

Uncertainties associated with BMP assessment under GCC also come from the procedures of scaling up. BMP monitoring typically carries out at plot or field scale. However, findings at the plot or field scale may not properly represent the BMP effectiveness at a watershed or regional scale, particularly for extreme events. For example, the transport of pollutants may take minutes to hours in overland flow, and hours to days in stream flow, whereas leaching to groundwater followed by discharge to a stream may take months to decades. Uncertainties arise on how to properly scale up BMP effects from plot and field scales to the watershed scale. These uncertainties would accumulate in a nonlinear manner from one step to the next. In summary, uncertainties associated with BMP assessment under GCC are of various types and at different levels. Because many of these uncertainties are either unknown or not well defined, it would be very challenging to accurately identify the uncertainties of BMP performance under GCC. Considering the difficulties we are facing in reliable and precise uncertainty analysis for hydrologic and BMP models, future climate change would make the process more complicated in identifying overall BMP uncertainties for policy making.

6. Concluding Remarks

GCC has become one of the critical and important environmental issues facing society today. BMPs are important measures for adapting to future climate change and mitigating adverse environmental impacts. The possible changes in future water availability, magnitudes of NPS pollution, and BMP effectiveness have to be accounted for in watershed planning and management. Lots of difficulties arise in properly assessing the BMP effects using modeling techniques. Part of these difficulties comes from our limited scientific understanding of BMP performance that is associated with complex hydrologic and climatic processes, their mutual interactions, and their variations under climate change. GCC may augment the frequency and severity of flooding and drought in different areas, and consequently affect BMP performance on water quantity and water quality at different spatial scales. Some of these BMPs may be not functional or cause negative impacts on water quality in specific areas under extreme events. Therefore, it is necessary to develop and apply proper modeling techniques in BMP assessment to address the potential risk of BMP failure under GCC.

It is evident that there remain considerable research challenges and opportunities in assessing BMP effects under GCC, such as developing reliable climate scenarios, adapting or developing models to account for extreme events, assessing BMP effects at multi-scales and with multi-objectives, and identifying uncertainties of BMP evaluation as proposed in this paper. Much can be learnt from BMP studies through the development of adequate information, thorough understanding, realistic analysis, and comprehensive evaluation techniques.

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