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Modeling the potential impacts of climate change on streamflow in agricultural watersheds of the Midwestern United States

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SUMMARY

The ability to predict spatial variation in streamflow at the watershed scale is essential to understanding the potential impacts of projected climate change on aquatic systems in this century. However, problems associated with single outlet-based model calibration and validation procedures can confound the prediction of spatial variation in streamflow under future climate change scenarios. The goal of this study is to calibrate and validate a distributed hydrologic model, the Soil and Water Assessment Tool (SWAT), using distributed streamflow data (1978–2009), and to assess the potential impacts of climate change on future streamflow (2051–2060 and 2086–2095) for the Rock River (RRW), Illinois River (IRW), Kaskaskia River (KRW), and Wabash River (WRW) watersheds in the Midwestern United States, primarily in Illinois. The potential impacts of climate change on future water resources are assessed using SWAT streamflow simulations driven by projections from nine global climate models (GCMs) under a maximum of three SRES scenarios (A1B, A2, and B1). Results from model validation indicate reasonable spatial and temporal predictions of streamflow, suggesting that a multi-site calibration strategy is necessary to accurately predict spatial variation in watershed hydrology. Compared with past streamflow records, predicted future streamflow based on climate change scenarios will tend to increase in the winter but decrease in the summer. According to 26 GCM projections, annual streamflows from 2051 – 2060 (2086–2095) are projected to decrease up to 45.2% (61.3%), 48.7% (49.8%), 48.7% (56.6%), and 41.1% (44.6%) in the RRW, IRW, KRW, and WRW, respectively. In addition, under the projected changes in climate, intra- and inter-annual streamflow variability generally does not increase over time. Results suggest that increased temperature could change the rate of evapotranspiration and the form of precipitation, subsequently influencing monthly streamflow patterns. Moreover, the spatially varying pattern of streamflow variability under future climate conditions suggests different buffering capabilities among regions. As such, regionally specific management strategies are necessary to mitigate the potential impacts of climate change and preserve aquatic ecosystems and water resources.

1. Introduction

The services provided by aquatic systems are fundamentally important to humans. In addition to providing clean water for consumption and agriculture, aquatic ecosystems sustain biodiversity and provide support for basic ecological processes as well as important economic activities, including fisheries and recreation. Nevertheless, aquatic systems are heavily impacted by human activities including land use changes associated with agriculture and urbanization, as well as physical modification to river channels which result in altered flow regimes (Miltner et al., 2004; Paul et al., 2006; Sullivan et al., 2006). In addition, the Earth's climate is predicted to exhibit significant changes in temperature and precipitation during this century due to human activities (Hansen et al., 2006). These expected climatic changes have been detected and already have resulted in measurable impacts on the physical environment (IPCC, 2007).

Increased temperature is the most commonly identified issue regarding predicted changes in climate during the coming century, and the potential impacts of this warming have received the majority of attention (IPCC, 2007). Changes in precipitation patterns are anticipated to be a significant component of climate change as well. Modifications of precipitation patterns including the changes in the magnitude and temporal variability of annual precipitation may result in relatively intense rainfall concentrated during particular times of the year (Kattenberg et al., 1996). Changes in precipitation, in combination with increases in temperature, can have dramatic effects on the

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hydrology of aquatic systems, subsequently impacting water resources as well as the aquatic taxa which are adapted to particular flow regimes (Poff et al., 1997).

Accurate information on the spatial variation in streamflow and the assessment of the potential impacts of climate change on future streamflow regimes are critical for water resource management, particularly in the context of water quantity, quality, and aquatic ecosystem sustainability. The coupling of hydrologic models with global climate models (GCMs) makes the assessment of climate change impacts on water resources possible. Previous studies have examined the impacts of future climate projections downscaled from GCM simulations on water resources (Cherkauer and Sinha, 2010; Hay et al., 2011; Jha et al., 2006, 2004; Kang and Ramirez, 2007; Lettenmaier et al., 1999; Nijssen et al., 2001; Takle et al., 2005). However, most of these studies have focused on the change in the overall water budget rather than the spatial and temporal changes in streamflow variability. Streamflow magnitude and variability are both essential variables influencing the survival, growth, and reproduction of aquatic species, and the directional alteration of these variables can impact local community structure and cause populations to decline (Bain et al., 1988).

Hydrologic models used to predict future water resources under projected warming should accurately reproduce observed streamflow through calibration (Duan et al., 1993; Gupta et al., 1998; Sivapalan et al., 2003; Wagener et al., 2007). A significant challenge in calibration is the identification of appropriate model parameters for distributed hydrologic models. In contrast to lumped models, distributed models account for watershed spatial heterogeneity by using a relatively larger number of parameters. However, not all parameters are measureable because the scale of measurement is usually smaller than the effective scale at which the parameters are applied (Beven, 2001b).

When models are comprised of a relatively large number of parameters, the issue of equifinality is a major concern (Beven, 1993, 2001a; Lo et al., 2010, 2008). That is, multiple sets of parameter combinations can yield similar results. Moreover, distributed hydrologic models can potentially amplify the problems associated with parameter estimations if spatially distributed data are unavailable for calibration. In this case, model calibration usually relies on measured hydrologic responses at a single watershed outlet (Githui et al., 2009; Rouhani et al., 2007; Zhan et al., 2006), such that the phenomenon of "predicting the correct result for the wrong reasons" may occur (Jetten et al., 2003). Though distributed hydrologic models are widely used, there are still very few extensive calibration and validation studies against distributed ground measurements in both water quantity and quality modeling (Beven, 2002). To reduce the possibility of apparently accurate simulations at the watershed outlet resulting from a combination of locally inaccurate simulations, multi-site calibration within a watershed is recommended (Gul and Rosbjerg, 2010; White and Chaubey, 2005; Zhang et al., 2010).

The goal of this study is to predict spatial variation of streamflow and assess the potential impact of climate change on streamflow in watersheds located primarily in Illinois in the Midwestern United States. A distributed hydrologic model, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), was calibrated and validated with measured streamflow from multiple gauged sites. The Sequential Uncertainty Fitting Algorithm (SUFI-2) (Abbaspour et al., 2004, 2007) was used for model calibration, validation, and uncertainty analysis. After the SWAT model was calibrated and validated, 26 biased-corrected and spatially downscaled future climate projections derived from nine GCMs were used to drive the validated SWAT model in order to assess the potential impacts of climate change on water resources in the studied watersheds.

2. Materials and methods

2.1. SWAT hydrologic model

SWAT is a physically-based and distributed hydrologic model developed to predict the impacts of changes in landscape management practices on water, sediment, and agricultural chemical yields (Arnold et al., 1998). In addition, SWAT is capable of assessing the impacts of climate change on hydrologic responses and agricultural activities by adjusting climatic variables based on future projections (Arnold and Fohrer, 2005; Neitsch et al., 2005a,b). SWAT typically operates on a daily time step for long-term simulations at large watershed scales. SWAT accounts for spatial heterogeneities by first dividing a large watershed into several sub-basins, and then further dividing the sub-basins into multiple hydrologic response units (HRUs). Each HRU is a combination of unique soil, land cover and management strategies. The simulated water quantity and quality from each sub-basin are routed by streamflow and distributed to the watershed outlet. For a more detailed description of SWAT, see Neitsch et al. (2005b).

2.2. Calibration and uncertainty analysis using SUFI-2

Due to the processes resulting in equifinality (Beven and Binley, 1992), it is difficult to manually calibrate a distributed model in which there are numerous parameters influencing the simulated hydrologic response. The SUFI-2 algorithm was used to assist model calibration, validation and uncertainty analysis (Abbaspour et al., 2004, 2007). Compared with similar techniques such as the Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992), Parameter Solution (ParaSol) (van Griensven and Meixner, 2006), and Bayesian inference methods (Kuczera and Parent, 1998), SUFI-2 requires fewer simulations to achieve a similar level of performance (Yang et al., 2008). Instead of identifying absolute parameter values, the characterization of parameter ranges is more important (Bardossy and Singh, 2008). Starting with the initial parameter ranges, SUFI-2 is capable of generating different parameter combinations, comparing simulations with observations, and identifying the optimal parameter ranges. Moreover, instead of calibrating model parameters based on hydrologic responses from a single watershed outlet, SUFI-2 is able to simultaneously calibrate parameters based on distributed data within a watershed. Hydrologic models cannot avoid uncertainties originating from input data, parameters, and model structures (Abbaspour et al., 2007; Dillah and Protopapas, 2000; Dubus and Brown, 2002; Leenhardt, 1995; Zhang et al., 1993). However, SUFI-2 maps all uncertainties onto the parameter ranges and quantifies overall uncertainty in the output of hydrologic response using a 95% prediction uncertainty (95PPU), which, in this study, was calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through the Latin hypercube sampling technique (Abbaspour et al., 2007). Moreover, SUFI-2 quantifies the uncertainties using *P-factor* and *R-factor* statistics. *P-factor* is the percentage of measured data falling into the 95PPU confidence interval, whereas *R-factor* is the average breadth of the 95PPU band divided by the standard deviation of measured data. The goal of SUFI-2 is to include the majority of measured data with the smallest possible uncertainty bands.

2.3. Study area and data

The study area consists of four watersheds: the Rock River watershed (RRW), Illinois River watershed (IRW), Kaskaskia River watershed (KRW), and Wabash River watershed (WRW) (Fig. 1). All four watersheds are located east of the Mississippi River, primarily