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Hydrologic response to climatic variability in a Great Lakes Watershed: A case study with the SWAT model

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Summary Process-based hydrologic models are usually calibrated prior to application to ensure that they closely match reality. However, different hydrologic response to varied climatic conditions might affect model calibration and validation. A case study was conducted for a 901 km^2 watershed of northern Michigan to compare the effects of calibrating the Soil and Water Assessment Tool (SWAT) watershed model with different climatic datasets representing drought (1948–1949) versus average (1969–1970) conditions. The effects of the different climatic conditions on parameter response and sensitivity were evaluated, and performance of the two calibration versions was compared using a common validation period, 1950–1965. For the drought- and average-calibration periods, models were well calibrated, as indicated by high Nash-Sutcliffe efficiency coefficients ($E = 0.8$ and 0.9), and low deviation of discharge values ($D = 2.9\%$ and 3.4%). Evapotranspiration parameters differed under the two sets of climatic conditions. The plant water uptake compensation factor (EPCO), appropriately reflected plant water uptake patterns in varied climatic conditions. Snow melting parameters differed between the two scenarios. A comparison of baseflow values simulated by SWAT versus those computed by a hydrograph separation method showed that the SWAT method treated most snowmelt as surface runoff, whereas the latter method treated much of it as baseflow. The drought-calibrated version of the model performed much better during the validation period (1950–1965) ($E = 0.8$, $D = 2.6\%$) than did the average-calibrated version ($E = 0.4$, $D = 41.4\%$).

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Introduction

Watershed models are essential for studying hydrologic processes and their responses to both natural and anthropogenic factors, but due to model limitations in representation of complex natural processes and conditions, models usually must be calibrated prior to application to closely match reality (Bastidas et al., 2002; Xu, 2003). An ideal hydrologic calibration set would include combined climatic conditions of dry, average, and wet years. In practice, however, hydrologic models are calibrated based on average climate condition, or the best available data (Van Liew and Garbrecht, 2003). During times of climate variability, a model calibrated for past climatic conditions may not be suitable under future, altered conditions. Validation of the calibrated model is typically done by comparing simulated with measured stream flow values. In addition to total surface stream flow, the validation of several hydrologic components, especially surface and groundwater flow and their responses to climatic conditions, is also needed in the development of distributed hydrologic models, but such comparisons are much less common (Beven, 1995; Arnold and Allen, 1996; Chu and Shirmohammadi, 2004; White and Chaubey, 2005).

Discrepancies between simulated and measured data often occur, especially during extreme years or seasons (Singh et al., 2005; Rosenthal et al., 1995; Srinivasan et al., 1998; Mapfumo et al., 2004; Chu and Shirmohammadi, 2004; Govender and Everson, 2005). Singh et al. (2005) found that two commonly used hydrologic models overestimated stream flow during drought years by about 39–49%, and underestimated flow during the wettest year by 14–7.2%. Arnold et al. (2000) found that the Soil and Water Assessment Tool (SWAT) underestimated spring peaks and overestimated fall stream flow in the Upper Mississippi River basin, which they attributed to seasonal variation in ET and soil moisture condition, and snowmelt simulation. Govender and Everson (2005) found that the SWAT model performed better in average and dry years than in wet years on the east coast of South Africa due to poorly simulated evaporation. Reasons for such disagreement might come from different sources, such as limited understanding of physical mechanisms for hydrologic processes, model structure, spatial data limitation and measurement error, and sensitivity of individual components and hydrologic parameters in different climatic situations (Xu, 2003).

The SWAT model has been used as an effective tool to model impacts of climatic change on hydrologic and biogeochemical cycles in a variety of watersheds (Arnold et al., 1998). As a physically based model, SWAT uses hydrologic response units (HRUs) to describe spatial heterogeneity in land cover and soil types within a watershed. The model estimates relevant hydrologic components such as surface runoff, baseflow, evapotranspiration (ET), and soil moisture change for each HRU. SWAT also includes snow melting and lake/wetland algorithms, which make the SWAT model a candidate in northern glaciated regions.

In the glaciated watersheds of the Great Lakes region, hydrology is significantly related to occurrence of wetlands and lakes, overwinter snow accumulation, snow melting during spring, and surface and baseflow contributions. Individual hydrologic processes and parameters would vary in response to hydroclimatic conditions. In particular, climate variability can alter the depth of overwinter snow accumulation and timing of spring snowmelt, causing temporal shifts in surface runoff that alter the baseflow perceived through hydrograph partitioning techniques (e.g., Holtschlag and Nicholas, 1998). The unique physiographic features in the region provide an excellent opportunity for hydrologic model evaluation.

A case study was conducted for a 901 km^2 watershed of northern Michigan to compare the effects of calibrating the SWAT model with different climatic datasets representing drought (1948–1949) versus average (1969–1970) conditions. The effects of the different climatic conditions on parameter response and sensitivity were evaluated, and performance of the two calibration versions was compared using a common validation period, 1950–1965. The purpose of this study is to (1) examine the responses of evapotranspiration, snow melting, and lake/wetland algorithms in the two climatic conditions (drought and average) by calibrating the SWAT model to two different climatic conditions, and (2) assess baseflow component and its seasonal patterns in these two climatic situations in the Upper Peninsula of Michigan.

Methods

Site description

The 901 km^2 watershed of the South Branch Ontonagon River (USGS gauging station 04039500 at Ewen, MI) was selected for study. The watershed is part of the 3460 km^2 Ontonagon River drainage basin, which flows into Lake Superior. Covering portions of Ontonagon and Gogebic Counties in the upper peninsula of Michigan and Vilas County in northern Wisconsin, the watershed extends 27 km in east–west direction and 46 km in north–south direction. The river drains northward, from an elevation of 550 m in the headwaters to 340 m at the gauging station (Fig. 1).

The watershed lies in the cold temperature region, and its weather is affected by local and regional climatic influences, particularly the effect of Lake Superior on temperature and precipitation. Annual precipitation observed between 1938 and 2005 ranged from 800 mm to 1000 mm with considerable spatial and temporal variation (Wu et al., 2006). Annual precipitation, especially lake-effect snowfall, is greatest near the shore of Lake Superior and decreases with distance inland from the shoreline. July receives the greatest rainfall during a year (80–130 mm), while January and December showed the greatest snow fall. The greatest mean daily snowfall (45 mm in January) occurred in Ontonagon, Ontonagon County (8 km from the lake shore) and the least (18 mm in January) occurred in Watersmeet, Gogebic County (64 km from the lake shore).

Annual average air temperature observed between 1938 and 2005 ranged from −2.5 °C to 0 °C, with highest in July (mean = 13 °C) and lowest in January (mean = −17 °C: Wu et al., 2006). Mean air temperature is over 0 °C from May through October, and it is below the freezing point for the other six months from November through April. With monthly average air temperature near zero and daily air temperature fluctuating either above or below 0 °C in April and October, these two months are the most hydrologically sensitive periods in the watershed (Wu et al., 2006).