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Assessment of climate change impacts on hydrology and water quality with a watershed modeling approach

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HIGHLIGHTS

► SWAT was modified by incorporating CO_2 impacts and stream temperature prediction.
► Updated SWAT was applied to watersheds in California under climate change scenarios.
► Evapotranspiration response to CO_2 concentration varied with vegetation type.
► Unfavorable conditions for cold-water species were predicted for future California.

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ABSTRACT

The assessment of hydrologic responses to climate change is required in watershed management and planning to protect water resources and environmental quality. This study is designed to evaluate and enhance watershed modeling approach in characterizing climate change impacts on water supply and ecosystem stressors. Soil and Water Assessment Tool (SWAT) was selected as a base model, and improved for the CO_2 dependence of potential evapotranspiration and stream temperature prediction. The updated model was applied to quantify the impacts of projected 21st century climate change in the northern Coastal Ranges and western Sierra Nevada, which are important water source areas and aquatic habitats of California. Evapotranspiration response to CO_2 concentration varied with vegetation type. For the forest-dominated watersheds in this study, only moderate (1–3%) reductions on evapotranspiration were predicted by solely elevating CO_2 concentration under emission scenarios A2 and B1. Modeling results suggested increases in annual average stream temperature proportional to the projected increases in air temperature. Although no temporal trend was confirmed for annual precipitation in California, increases of precipitation and streamflow during winter months and decreases in summers were predicted. Decreased streamflow during summertime, together with the higher projected air temperature in summer than in winter, would increase stream temperature during those months and result in unfavorable conditions for cold-water species. Compared to the present-day conditions, 30–60 more days per year were predicted with average stream temperature >20 °C during 2090s. Overall, the hydrologic cycle and water quality of headwater drainage basins of California, especially their seasonality, are very sensitive to projected climate change.

1. Introduction

Effects of climate change on the hydrologic cycle and water quality of a watershed are associated with large uncertainty from both the climate projections and the hydrologic modeling approaches. The interaction between climatic variables and hydrologic components involves multiple competing processes. For example, elevated concentration of atmospheric CO_2 has direct impacts on plant transpiration, which further alters the magnitude and seasonality of hydrologic components in the watershed. Studies indicated reduction of leaf stomatal conductance under high CO_2 concentration, suggesting a decrease of potential evapotranspiration (PET) (Medlyn et al., 2001; Morison, 1987; Wand et al., 1999). Conversely, there are evidences of positive relationship between CO_2 concentration and the total leaf area of a plant, i.e., elevated CO_2 concentration may also increase PET (Pritchard et al., 1999; Wand et al., 1999). In addition, CO_2 concentration also influences the rate of biomass production and thus shifts the plant growth pattern (Neitsch et al., 2011; Stockle et al., 1992). Therefore, the actual effects of elevated CO_2 concentration should be determined with consideration of local weather conditions. Similarly, in addition to its direct effects on stream temperature, higher air temperature is expected to increase PET and potentially decrease water yield to rivers, which further degrades the river water quality due to less dilution. However, global warming

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may also intensify hydrologic cycle and further lead to streamflow increase (Labat et al., 2004). While General Circulation Models (GCMs) together with greenhouse gas emission scenarios generate future climate data virtually for any place of the world, their implications for regional hydrologic cycle and environmental quality are yet poorly understood.

Watershed modeling approach has been widely used in translating the GCM-generated climate data to their potential effects and management implications on regional water resources. For example, modeling results of a lumped rainfall-runoff model (HSAMI) on the St. Lawrence tributaries, Canada, suggested higher winter discharges under climate change, which may induce important modifications of river hydrology and geomorphological processes to riparian ecosystem (Boyer et al., 2010). The Hydrologic Modeling System (HEC-HMS) was applied to the Siurana catchment, Spain, and indicated that the effects of climatic variables on future water resources was highly dependent on local soil moisture conditions (Candela et al., 2012). Climate sensitivity analysis for a hypothesized watershed in western Turkey was conducted based on Hydrological Simulation Program—Fortran (HSPF), and the authors concluded that seasonal variations of precipitation and temperature were very important in predicting the future response of watersheds (Göncü and Albek, 2010). More modeling efforts are based on the Soil and Water Assessment Tool (SWAT) with its built-in options for climate change studies. More than 80 papers have been published for SWAT applications under climate change scenarios for watersheds all around the world (https://www.card.iastate.edu/swat_articles/). SWAT is selected in this study as a base model to represent the climate change effects on hydrology and water quality simulations.

Streamflow and stream temperature are usually considered as representative variables in watershed management and planning. Streamflow is a comprehensive indicator of water resources and hydrologic processes in the drainage area. By relating to its components of surface runoff, lateral flow, and groundwater recharge, streamflow is also an important predictor variable for soil erosion and generation of other pollutants. In addition to physically based modeling of surface water quality, streamflow could be directly related to pollutant loadings in a river (Cohn, 1995; Runkel et al., 2004). Stream temperature itself is frequently included as one of the most important water quality indicators in surface water assessment such as the 303(d) listing by U.S Environmental Protection Agency (USEPA, 2011). It also has significant effects on in-stream biogeochemical variables/processes including algal growth, dissolved oxygen concentration, nutrient cycling and productivity, and chemical reaction kinetics (Ducharne, 2008; Mohseni et al., 2003; Ozaki et al., 2003). In addition, streamflow and stream temperature are major aspects of water quality for aquatic ecosystems, and affects the speciation and distribution of fish and other organisms. Reduced streamflow and/or higher stream temperature by human activity or climate change are related to the loss of formerly suitable habitats for native species (Dowling and Wiley, 1986; Harvey et al., 2006; Ligon et al., 1999; McCullough, 1999). Recently, there have been substantial research interests in assessing the impacts of projected climatic changes on stream temperatures and aquatic ecosystems (Ficklin et al., 2012a; Isaak et al., 2010, 2012; van Vliet et al., 2011; Webb et al., 2008). The determination of streamflow and stream temperature is therefore critical for the effective protection of water resources and water quality and the implementation of watershed management practices.

Two major issues have been identified for SWAT applications under climate change scenarios. First, the original SWAT inadequately represents the effects of CO_2 concentration on plant growth and associated transpiration estimation. The response of leaf stomatal conductance to the doubling of CO_2 concentration is described in SWAT with a reduction of 40% for all vegetation species, while the CO_2-induced increase of the maximum leaf area index (LAI) is not considered. In addition, only one value of CO_2 concentration is allowed for each set of SWAT simulation, limiting the model applications for continuous GCM data. Secondly, SWAT predicts stream temperature based on a simple linear relationship between air-water temperatures, which may not general reliable results for all watersheds. Efforts have been made to improve SWAT for some of the above issues (Eckhardt and Ulbrich, 2003; Ficklin et al., 2012a; Wu et al., 2012), but an integrated solution is not presented yet.

This study aims to update the original SWAT with more mechanistic responses of hydrologic components and stream temperature to climate change. In specific, (1) mathematic formulations are modified or added to SWAT to allow plant type-specific parameters in simulating the changes of stomatal conductance and leaf area index under elevated CO_2 level; (2) a hydroclimatological model for stream temperature prediction is developed and integrated into SWAT. The update SWAT model was applied to selected headwater drainage basins throughout California with historical weather condition (2001-2010) and downscaled GCM data (2001-2099). Results were analyzed for the model performance of streamflow and stream temperature, and their sensitivity to climatic variables.

2. Methods and materials

2.1. Soil and water assessment tool and its representations of changing climate

SWAT is a conceptual semi-distributed model developed by the United States Department of Agriculture (USDA) for watershed hydrology and water-quality operating on daily time step (Neitsch et al., 2011). In the model, the watershed of interest is divided into explicitly parameterized smaller areas of subbasins and enclosed hydrologic response units (HRUs). The HRUs are delineated by overlaying topography, soil, and land use maps, and assumed to be homogeneous with respect to their hydrologic properties. SWAT simulations can be separated into two major divisions of "land phase" for water and pollutant loadings to channels, and "routing phase" for in-stream water quantity and quality. A full description of SWAT can be found in Neitsch et al. (2011).

SWAT requires daily weather data as inputs. Climate change scenarios for precipitation, air temperature, and wind speed, therefore, can be easily reflected by manipulating the weather input files. In addition, SWAT allows user-defined monthly adjustments on precipitation, temperature, solar radiation, and humidity for each subbasin (input parameters of RFINC, TMPINC, RADINC, respectively, in the "sub" input files). In SWAT, CO_2 concentration can be also specified for each subbasin. CO_2 concentration is mainly used by SWAT to adjust the calculations of potential evapotranspiration and the biomass production. The effects of elevated CO_2 level on PET estimation will be discussed in the next section. For biomass production, SWAT adjusts radiation-use efficiency (RUE, kg/ha/[MJ/m^2]) for elevated atmospheric CO_2 concentrations (Stockle et al., 1992),

$$RUE = \frac{100CO_2}{CO_2 + \exp(r_1 - r_2 \cdot CO_2)} \quad (1)$$

where CO_2 (ppm) is the atmospheric CO_2 concentration, and r_1 and r_2 (dimensionless) are shape coefficients derived from two known RUE values at the reference CO_2 concentration (330 ppm) and a higher concentration provided in the SWAT built-in crop database ("crop.dat").

2.2. Modifications on SWAT for climate change study

2.2.1. CO_2 effects on PET estimation

Two competing processes are involved for the effects of elevated CO_2 level on evapotranspiration (ET) from vegetation. With higher CO_2 concentration, less stomata opening is required to obtain the amount of CO_2 necessary for photosynthesis and reduce transpiration rate. At the same time, plant growth is stimulated by higher CO_2 concentration with increased apparent quantum yield of photosynthesis, resulting in higher maximum leaf area index (LAI) and transpiration.