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Assessment of climate change impacts on water balance components of Heeia watershed in Hawaii

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ABSTRACT

Study region: Heeia watershed, Oahu, Hawaii, USA.
Study focus: Hydrological models are useful tools for assessing the impact of climate change in watersheds. We evaluated the applicability of the Soil and Water Assessment Tool (SWAT) model in a case study of Heeia, Pacific-island watershed that has highly permeable volcanic soils and suffers from hydrological data scarcity. Applicability of the model was enhanced with several modifications to reflect unique watershed characteristics. The calibrated model was then used to assess the impact of rainfall, temperature, and CO_2 concentration changes on the water balance of the watershed.
New hydrological insights for the study region: Compared to continental watersheds, the Heeia watershed showed high rainfall initial abstraction due to high initial infiltration capacity of the soils. The simulated and observed streamflows generally showed a good agreement and satisfactory model performance demonstrating the applicability of SWAT for small island watersheds with large topographic, precipitation, and land-use gradients. The study also demonstrates methods to resolve data scarcity issues. Predicted climate change scenarios showed that the decrease in rainfall during wet season and marginal increase in dry season are the main factors for the overall decrease in water balance components. Specifically, the groundwater flow component may consistently decrease by as much as 15% due to predicted rainfall and temperature changes by 2100, which may have serious implications on groundwater availability in the watershed.

1. Introduction

Island communities, including those of the Hawaiian Islands, rely on local water resources, which may be very sensitive to climate change (Pulwarty et al., 2010). Yet, future prediction of the state of water resources at a scale of a typical island watershed is hampered by the small geographical area of the island, which is not resolved in climate models, and by the scarcity of hydrological data that are needed to capture variability within such a watershed. While the integrated assessment of hydrology and climate has been getting increased attention in the field of hydrology and related disciplines (Wilby et al., 2006), there are very few studies on expected changes in water budgets in small island watersheds (Safeeq and Fares, 2012).

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Evidence of climate change in Hawaii includes historical observations of temperatures and sea- level data, which show increasing trend as a result of warming climate (Firing et al., 2004; Giambelluca et al., 2008; Diaz et al., 2011). Globally, researchers have reported that extreme climate change may cause frequent incidents of flooding and drought, shortage of water supply, landslides, soil erosion, and damage to existing infrastructures (Beniston et al., 2007). Some of these problems have already been documented in Hawaii. For example, baseflow and streamflow of Hawaiian streams have showed a decreasing trend due to a combined effect of increasing groundwater withdrawals and lower precipitation (Oki, 2004; Bassiouni and Oki, 2013).

Recent studies on climate change have shown that rainfall over the Hawaiian Islands is expected to decrease during the nominal wet season (November to April) but marginally increase during the dry season (May to October) (Timm and Diaz, 2009; Timm et al., 2011). Given that approximately 70% of the annual rainfall happens during the wet season, Hawaii is expected to face an overall reduction in annual rainfall leading to a decline in sustainability of groundwater recharge (Burnett and Wada, 2014). In addition, Diaz et al. (2011) and Giambelluca et al. (2008) reported that air temperature in the Hawaiian Islands is anticipated to increase in the future. Such an increase will influence components of the hydrologic cycle as it drives evapotranspiration. Other factors negatively influencing water resources include population growth (http://uhero.prognoz.com/TableR.aspx) and water demand increase (Engott et al., 2015). With such expected problems, climate change simulations and analysis of its anticipated impacts on hydrological processes are invaluable tools in the design and planning of mitigation measures to address the adverse consequences of climate change.

The general procedure for assessing the impacts of climate change on water resources and watershed processes is first to project plausible future climate change scenarios through the use of Global Climate Models (GCMs). Recently, different GCMs of the Coupled Model Intercomparison Project Phase 5 (CMIP5) have been developed for future climate change projections, which are based on Representative Concentration Pathways (RCPs) of greenhouse gases by 2100 (IPCC, 2014). The GCMs determine the effects of changing concentrations of greenhouse gases on global climate variables, such as temperature, rainfall, evapotranspiration, humidity, and wind speed. However, the direct use of GCMs' outputs for local scale hydrologic analysis can result in inadequate model outputs, due to their coarse spatial and temporal resolutions (Elsner et al., 2010). Therefore, the results of the GCMs should be downscaled to either regional or local scale through the use of statistical or dynamical downscaling techniques (Salathe et al., 2007; Timm and Diaz, 2009). In the following step, spatially semi-distributed, physically-based hydrological models, such as the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), can be used to examine and assess the impacts of climate change (Bae et al., 2011). Due to its wide utility and applicability, different versions of SWAT have been used for several studies throughout the world (Krysanova and Arnold, 2008; Gassman et al., 2014). SWAT has been used for hydrological modeling (Ndomba et al., 2008a,b; Thampi et al., 2010; Notter et al., 2012; Strauch et al., 2012; Kumar et al., 2014; Abbaspour et al., 2015; Leta et al., 2015; Nyeko, 2015; Yen et al., 2016), soil erosion and sediment transport modeling (Ndomba et al., 2008a,b; Betrie et al., 2011), climate change impact studies on streamflow (Githui et al., 2009; Mango et al., 2011), and land use change and management practices impact assessment on streamflow and sediment yield (Betrie et al., 2011; Mango et al., 2011). In addition, SWAT has been internationally used for tile-drain, nutrients transport, and pesticide modeling with (out) model modifications, especially in lowland agricultural watersheds (Koch et al., 2013; Moriasi et al., 2013; Bannwarth et al., 2014; Fohrer et al., 2014; Bauwe et al., 2016; Cho et al., 2016; Golmohammadi et al., 2016). The previous studies confirm the successful use of SWAT across a broad range of watershed scales, environmental problems, hydrologic and pollutant conditions.

While previous studies on watershed hydrologic modeling focused on continental watersheds, there is a need to test the applicability of SWAT for pacific island watersheds that are characterized by relatively small-scale, steep topography, large precipitation gradients, volcanic rock outcrops, and scarcity of data. These characteristics are typical for the Hawaiian watersheds and there are only a few applications of other hydrological models (Sahoo et al., 2006; Apple, 2008; Safeeq and Fares, 2012), which were mainly focused on the dryer, leeward side of the island of Oahu, Hawaii. An exception is Apple (2008) who evaluated the applicability of Hydrologic Simulation Program-Fortran (HSPF) for Kaneohe watershed, which is located in the wet, windward section of the island. She concluded that the HSPF model produced acceptable results for annual and monthly streamflow simulations, but daily streamflow predictions were not accurate. Thus, a need exists for watershed model development in the windward, wet side of the islands that will be very sensitive to climate change, as an essential task for an integrated water resources management, climate change impact assessment, and adaptive strategy to climate change.

The specific objective of this study was to illustrate that a watershed model can be applied for water balance analysis in highly permeable (volcanic soils) watershed with challenging characteristics not yet captured or addressed in existing studies and that a model can be applied for water balance analysis in future climate change scenarios. This study addressed this objective in two steps:

a) evaluate the applicability and suitability of the SWAT model for streamflow simulations in Heeia under scarcity of hydrological data;
b) assess the impact of three different climate variables (rainfall, temperature, and CO_2 concentration) change on the water balance components in the watershed.