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Research paper

Curve number modifications and parameterization sensitivity analysis for reducing model uncertainty in simulated and projected streamflows in a Himalayan catchment

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A R T I C L E I N F O

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A B S T R A C T

Climate essentially controls the supply of ecosystems, species ranges, and process rates on Earth. Modeling hydrological processes for hilly catchments dominated by snow cover and glaciers is complex and relies on improved calibration and uncertainty analysis methods to standardize the watershed based ecosystem management practices. In this study, a modified curve number (CN) approach has been employed to simulate streamflow and water yield at sub-catchment scale over hundred years utilizing Soil and Water Assessment Tool (SWAT), which relies on the main physical factors of the ecosystem such as landuse/landcover and soil. The model calibration and validation strength was evaluated using coefficients of determination (R^2) and Nash-Sutcliffe Equation (NSE) objective functions. The uncertainties (percentage) occurred in the modeled streamflow were estimated using two optimization algorithms such as the Sequential Uncertainty Parameter Fitting Approach (SUFI2) and the Parametric Solution (ParaSol). A parameterization based sensitivity analysis was carried-out to recognize the most influencing model calibration parameters. Statistical downscaling of daily temperature and precipitation datasets was performed utilizing Coupled Model Intercomparison Phase Five (CMIP5) Global Circulation Models (GCMs) with their Representative Concentration Pathway (RCP) experiments. The downscaled temperature and precipitation were utilized to assess the climate change impact on streamflows at sub-catchment scale. The historical and projected scenarios of streamflow (at the outlet) and water yield (at sub-catchment scale) showed substantial variabilities in their amount in both temporal (1991–2100) and spatial scales (sub-catchment 1 to sub-catchment 7). The magnitude of change analysis confirmed a substantial increase in the water yield across all the sub-catchments over Himalaya. The percent of change analysis ensured that the magnitude of change of water yield is highly vulnerable in the Himalayan catchments. The GCMs based projected scenarios demonstrated a consistent increase in the streamflow at both outlets (e.g. Lachung and Chungthang). The overall results show a consistent increase in precipitation and water yield amount over the Himalayan catchments. The variable streamflow in terms of amount and intensity may disrupt the ecosystem services in the Himalayan catchments.

1. Introduction

Due to increments in the air temperature, the vapor carrying capacity is significantly affected across the world (Collins et al., 2013). The exponential rate of change of air temperature has been identified as one of the main causes of climate change (Taylor et al., 2012). The variations in the ratio of precipitation to snowfall and rainfall are increasing non-uniformly around the world (Chamaille-Jammes et al., 2007). A non-uniformity in the precipitation events and amount observed (Khadka et al., 2014). Extreme events will be more frequent in the Himalayan region in coming years (Shivam et al., 2016; Singh and Goyal, 2016; Singh et al., 2015). The Himalayan glacier ranges are the largest and most dynamic in the world (Pachauri et al., 2014; Collins et al., 2013). Several studies reported that the glaciers have been retreating since the end of the Little Ice Age (LIA) and they have been accelerated since 1970s (e.g. Collins et al., 2013). The earlier and accelerated melting rate of permanent snow covers and glaciers are contributing more water to the rivers (Collins et al., 2013). The earlier melting of snow-glaciers due to climate change have largely affected the seasonality and quantity of streamflow over Himalayan watersheds (Collins et al., 2013; Kulkarni et al., 2010). Many studies reveal that the Himalayan glaciers have been losing their mass and are shrinking

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(Pachauri et al., 2014; Khadka et al., 2014; Krishna, 2005) and that the flow of Himalayan rivers is increasing (Singh et al., 2015). Thus the downstream portions of the rivers are flooding (Radic et al., 2014; Kulkarni et al., 2010).

The eastern Himalayas is recognized as one of the most fragile ecosystems in the world. The poor and marginalized people living in this region face a pressing challenge of adapting to changing climate (Chettri et al., 2009). The shifts in rainfall and snowfall pattern over Himalayas due to climate change will affect the habitat of many species (Chakraborty et al., 2016). In particular, Chettri et al. (2009) and Huss (2011) conducted studies on the Himalaya and found that glaciers in this region have shrunk and the permanent snow cover is significantly decreased. The relative contribution of discharge from glaciers has decreased and the yearly peak discharge has shifted towards spring. Collins et al. (2013) worked on the climatic variations in Himalayan region and deduced that discharge of Ganges river, especially in Nepal, significantly fluctuated. However, the level of flow was usually preserved from the 1960s to 2000s. Bhutiyani et al. (2008) found that the discharge of the Satluj river significantly increased from the year 1991–2004 due to enhanced temperature warming. Bhambri et al. (2011) concluded that the snowmelt induced runoff will be higher in the 21st century over the Himalayan region and that could affect the aquatic ecosystems in Himalayas.

Distributed and deterministic eco-hydrological models have been effectively utilized for the management of water resources. The physical and real time meteorological parameters based hydrological models were found more reliable for the computation of water balance than other modeling approaches (Singh et al., 2013a,b; Abbaspour, 2011; Arnold et al., 2012). The hydrological response unit (HRU) scale based semi-distributed hydrological model Soil and Water Assessment Tool (SWAT) and stochastic optimization tool SWAT Calibration and Uncertainty Program (SWATCUP) have already proven their utilities in various water balance studies around the world (Singh et al., 2013b; Abbaspour, 2011; Schuol et al., 2008; Gosain et al., 2006). To incorporate the present climate projections (e.g. Global Circulation Models: GCMs), we emphasized that the present modeling framework should be defined and explained (Li et al., 2015; Vermote, 2015; Slater et al., 2009; Molotch and Margulis, 2008). We highlighted the need to parameter optimization algorithms and uncertainty analysis to generate more accurate projection scenarios of main hydrological components such as streamflow, water yield and precipitation.

The Teesta river in the eastern Himalayas is characterized by extremely high elevation ranges (e.g. 1400 m to 7400 m, approximately) (Singh and Goyal, 2016). The topography is dominated by snow cover, glaciers and steep slopes (Singh and Goyal, 2016). In previous SWAT based studies, several authors reported unusual high peaks in modeled streamflows, especially when modelling hilly terrain. The high peak in the compute discharge may be occurring due to steep slopes. It is found that this problem is very common in the curve number (CN) based runoff computation (Rahman et al., 2013; Schilling et al., 2008). The unreliable high flow peaks may enhance the uncertainty level, which further makes calculating of water balance unreliable (Singh et al., 2015; Mishra et al., 2014). This will tend to increase an uncertainty level in the projection of water balance components such as water yield and snowfall/snowmelt (Schulz et al., 2008). This could affect the downstream movement of streamflow and may affect the aquatic life of the living species.

The SWAT model has proven its suitability for the calculation of in the projection of water balance components in large river basins across the world (Singh et al., 2015; Schuol et al., 2008; Gosain et al., 2006; Arnold et al., 2012). Gosain et al. (2006) used SWAT for simulating twelve large river basins in India to quantify the climate change impact on hydrology and concluded that the future discharge volume has been enhanced for those rivers originating from the Himalayan glaciers due to the higher melting rate of snow and glaciers. Schuol et al. (2008) used SWAT to analyze the hydrology of the entire Africa continent at sub-catchment spatial scales in the monthly time intervals. Schuol et al. (2008) found a significant variability in the discharge amount during historical and future time domains. In this study, the rainfall-runoff relationship based Soil Conservation Services (SCS) curve number (CN) method utilized for the computation of accurate streamflow discharge (Mishra et al., 2014; Neitsch et al., 2011).

As model uncertainties reduce the confidence level of projection scenarios, the prime objective of this study was to implement the modified CNs in SWAT at a HRU scale by the computation of fractional slopes. The fractional slopes are computed at each hydrological response unit (HRU) scale and then the CNs are adjusted for each HRU to avoid the slope steepness, especially over hilly catchment (Jain et al., 2010). The deterministic models do not compute randomness (Singh et al., 2013a,b). This study incorporates stochastic advance optimization algorithms such as Sequential Uncertainty Parameter Fitting Approach (SUFI2) and Parametric Solution (ParaSol) (Abbaspour, 2011; Abbaspour et al., 2007). The results from both methods are compared to find out the suitability of the optimization methods for hilly catchments. The parameter based sensitivity analysis was done to find out the most influencing parameter over snow glacier induced Teesta river catchment (Singh et al., 2013a,b; Abbaspour, 2011). The optimization algorithms are found helpful to reduce various kinds of model uncertainties (e.g. parameter uncertainty, input data related uncertainties and model structure uncertainty) in calibrated and projected modeling outcomes (Singh et al., 2015, 2013a,b; Abbaspour et al., 2011).

Another objective of this study was to evaluate the effects of climate change in the projected water yield and streamflows over the snow-glacier induced Teesta river Himalayan catchment. The projection scenarios were generated utilizing the Coupled Model Intercomparison Project Phase Five (CMIP5) Global Circulation Models (GCMs) with their Representative Concentration Pathway (RCP) experiments (Taylor et al., 2012). The projected streamflow and water yield are characterized at each sub-catchment scale to highlight the spatial variations due to climate change. The annual surface runoff and water yield were analyzed at each sub-catchment scale in the future time domain to assess increase and decrease in their amount. The percentage of change analysis was conducted to determine the magnitude of change of water yield at each sub-catchment scale, which may be useful to highlight the stress over watershed ecosystem and their components in a Himalayan region even at smaller scales. The Teesta river catchment has very diverse ecology and thus the any change in streamflow and water yield with respect to glaciered and non-glaciered portions may affect the biodiversity of the region.

2. Study area description

The Teesta river catchment (up to Chungthang gauge) part of Indus river basin has been selected for the analysis, which is a part of eastern Sikkim Himalaya India. The flow in the Teesta river originates from many small and large tributaries. Lachung river is one of the major tributaries of Teesta river joins the Teesta river at Chungthang gauge and also contributed a significant amount of flow in the downstream of Teesta river. The Teesta river originates from the Chhombo Chhu and Khangchun Chho glacial lakes. These lakes are situated at an elevation of 5280 m (Krishna, 2005). Many small tributaries meet the Teesta river on the eastern flank and several larger tributaries meets Teesta on the western flank. These tributaries contributed a large amount of drainage density. The Chungthang gauge point has been selected as the final outlet of the catchment (Fig. 1).

The two most important meteorological factors i.e. air temperature and precipitation show significant variation from downstream to upstream portions. The temperature decreases with increasing height referred to temperature lapse rate (TLR) and precipitation gradient (changes in precipitation from one location to another) significantly vary over the Teesta river catchment (Singh and Goyal, 2016). The downstream portion corresponds to moderate elevation ranges (e.g.

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