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Projected hydrologic changes in monsoon-dominated Himalaya Mountain basins with changing climate and deforestation

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SUMMARY

In mountain headwaters, climate and land use changes affect short and long term site water budgets with resultant impacts on landslide risk, hydropower generation, and sustainable agriculture. To project hydrologic change associated with climate and land use changes in the Himalaya Mountains, we used the Soil and Water Assessment Tool (SWAT) calibrated for the Tamor and Seti River basins located at eastern and western margins of Nepal. Future climate change was modeled using averaged temperature and precipitation for 2080 derived from Special Report on Emission Scenarios (SRES) (B1, A1B and A2) of 16 global circulation models (GCMs). Land use change was modeled spatially and included expansion of (1) agricultural land, (2) grassland, and (3) human settlement area that were produced by considering existing land use with projected changes associated with viability of elevation and slope characteristics of the basins capable of supporting different land use type. From these simulations, higher annual stream discharge was found for all GCM-derived scenarios compared to a baseline simulation with maximum increases of 13 and 8% in SRES-A2 and SRES-A1B for the Tamor and Seti basins, respectively. On seasonal basis, we assessed higher precipitation during monsoon season in all scenarios that corresponded with higher stream discharge of 72 and 68% for Tamor and Seti basins, respectively. This effect appears to be geographically important with higher influence in the eastern Tamor basin potentially due to longer and stronger monsoonal period of that region. However, we projected minimal changes in stream discharge for the land use scenarios potentially due to higher water transmission to groundwater reservoirs associated with fractures of the Himalaya Mountains rather than changes in surface runoff. However, when combined the effects of climate and land use changes, discharge was moderately increased indicating counteracting mechanisms of hydrologic yield in these mountains. Better understanding of potential hydrologic response to climate and land use changes in these basins might be crucial for national and transnational water management.

1. Introduction

The accessibility of clean water, as an essential ecosystem service, is a crucial component for sustainable management of a watershed system (Mark and Dickinson, 2008). This requirement has become more problematic due to changing climate and land management practices, specifically in the Himalaya Mountains where elevation ranges from 60 m above mean sea level to >8,000 m within a north–south distance of approximately 197 km (Hannah et al., 2004). This extreme elevation combined with potential climate and land use change affects streamflow in this unique mountain headwater system (Ma et al., 2010). For example, monsoon precipitation accounts for 80% of total input to this mountain range (Sharma, 1993) that may increase the risk of hydrological-related disasters such as flood and landslide in steep meandering channels. The risk is further enhanced by exposed rocks without vegetation cover located at higher altitude that increases surface runoff and sediment yield (Summerfield and Hulton, 1994; Ludwig and Probst, 1998). These events reduce the water supply and hydro-electricity generation as transported sediment lowers storage capacity of downstream reservoirs (Monirul and Mirza, 2003).

The South-Asian monsoon precipitation initiates from the south-eastern part of the Himalayan range and weakens toward north-western part so its contribution is substantial in eastern Himalayan region with glacier expansion during summer months

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(Asahi and Watanabe, 2004; Bookhagen et al., 2005). The western regions are predominantly influenced by winter westerlies causing snowfall at higher elevation with glacier advance during winter months (Barros et al., 2006). These climatic differences result higher snowmelt contribution (up to 50%) to the total annual stream discharge of far western Himalayan basins compared to eastern basins (~25%) (Bookhagen and Burbank, 2010). Therefore, these basins are likely to show different responses to continued climate change that potentially differentiate meltwater contribution to discharge of the rivers.

Extensive human-induced land use change is a major global research issue (Foley et al., 2005; Marshall and Shortle, 2005) that affects surface runoff, and stream discharge due to change in rainfall interception, evapotranspiration, and surface soil hydraulic conductivity (He et al., 2008; Germer et al., 2009; Scheffler et al., 2011; Munoz-Villers and McDonnell, 2013; Yan et al., 2013). Managing seasonal flood and river water quality influenced by different land-cover types has become a major challenge, though with little change in annual discharge value (Guo et al., 2008). In Nepal, high population growth has resulted in rapid land use changes, primarily destruction of forested land that directly influences the crop production of high mountain regions (Ives, 1987; Rai and Sharma, 1998; Kaltenborn et al., 2010). Land use change also affects downstream water availability of mountain basins (He et al., 2008; Nepal et al., 2014). Deforestation, specifically in Nepal, has become a major problem after the government's resettlement program that destroyed a total 103,968 ha of forests in Siwalik Hills and Terai plains from the 1950s to the mid-1980s (MPFS, 1988). This deforestation results in excessive fuelwood extraction, intensive livestock grazing, and expansion of agricultural land area. Land use change effects, specifically associated with deforestation, also have created social and political problems, mainly due to excessive water use by upstream farmers that changes in water supply to lowland areas (Walker, 2003).

Hydrological models are commonly used to study the effect of land management on the hydrological cycle, mainly focused on surface runoff processes (Karvonen et al., 1999; Felix et al., 2002). These models may include the representation of hydrological processes and associated water quality issues including sediment loading of surface water (Luo et al., 2008). The Soil and Water Assessment Tool (SWAT) is a quasi-distributed hydrological model that has been used to estimate climate change effect on stream discharge and groundwater recharge of mountain basins (Stonefelt et al., 2000; Eckhardt and Ulbrich, 2003; Gassman et al., 2007; Song and Zhang, 2012; Neupane et al., 2014). Some studies have also used the SWAT for assessing land use/management change effect on watershed hydrologic responses including surface runoff (Fohrer et al., 2001). However, only few studies have focused on the Himalaya Mountains for predicting future hydrologic response in changing climate and land use practices, primarily due to data scarcity. The major objectives of this study are: (1) to assess the inherent different climate influences on water budgets of two Himalaya Mountain basins that represent the east and west margins of Nepal, and (2) to evaluate potential climate change, land use change, and combined climate and land use change effects on future water availability of these basins through simulation modeling.

2. Materials and methods

2.1. Study site

For this study, we chose two Himalayan drainages located at eastern and western margins of Nepal including the Tamor River Watershed (TRW) and Seti River Watershed (SRW), respectively (Fig. 1). The Tamor River originates from Kanchanjunga Mountain and has a total catchment area of 6,111 km^2. The Seti River originates from Api and Saipal mountains with total catchment area of 7,379 km^2. These rivers are major headwater reaches that eventually feed the Ganges River. The elevation for the Tamor basin ranges from 139 to 8,422 m above mean sea level (amsl). For the Seti basin, elevation ranges from 327 to 7,043 m amsl. Geologically, the basins are composed of Paleozoic–Mesozoic Tethyan Sediment Series with metamorphic gneisses, migmatites, and Proterozoic sediments that form a fractured basement aquifer system which may significantly influence groundwater contribution to stream discharge of the basins (Andermann et al., 2012). The dominant soils of the basins, derived from the WaterBase project (http://waterbase.org/download_data.html), are Cambisols and Leptosols. Cambisols are moderately developed soils distributed at lower elevation with higher vegetation productivity, and Leptosols are shallow soils primarily distributed in the upper mountainous regions with steep slopes.

Nepal has three distinct climatic zones broadly based on elevation: the sub-tropical zone (<1,800 m), the temperate zone (1,800–4,000 m), and the alpine zone (>4,000 m) (Polunin and Stainton, 2000). However, the sub-tropical zone of western Himalayan region is limited to elevation of <1,400 m due to extreme colder winter months. At lower elevations, hot summers have daily temperature of 40 °C with total annual rainfall ranging from 1,500 to 2,000 mm (Ichiyanagi et al., 2007; Neupane et al., 2014). Cold and dry conditions are common at higher elevations with the average temperature and precipitation values of 11 °C and 257 mm, respectively (Pohle, 1991). While Nepalese watersheds are highly influenced by monsoonal precipitation, water budgets are mainly influenced by snowfall at higher elevations (Sharma, 1993).

2.2. Modeling approach

The study simulated runoff yield using ArcGIS interface of the SWAT (version 2009) (http://swat.tamu.edu/software/arcswat/) which is a river basin model developed for the U.S. Department of Agriculture (USDA) by Blackland Research Center in Texas (Arnold et al., 1998; Neitsch et al., 2009). The hydrological component of SWAT is based on the following equation.

$$SW_t = SW_0 + \sum (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (1)$$

where SW_t is the final soil water content (mm), SW_0 is the initial soil water content (mm), t is time in days, R_{day} is the amount of precipitation (mm), Q_{surf} is the amount of surface runoff (mm), E_a is the amount of evapotranspiration (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile (mm), and Q_{gw} is the amount of return flow (mm). We used the commonly applied runoff curve number method to estimate surface runoff in the basins (Loague and Freeze, 1985). Potential evapotranspiration (PET) was estimated using Penmann-Monteith procedure (Monteith, 1965) which is based on the energy balance components. The net water yield (WYLD in mm) to the stream channel was estimated using Eq. (2) as follows.

$$WYLD = SURQ + LATQ + GWQ - TLOSS \quad (2)$$

where $SURQ$ is the surface runoff (mm), $LATQ$ is the lateral flow contribution to stream discharge (mm), GWQ is the groundwater contribution to the stream discharge (mm), and $TLOSS$ is the transmission losses from the system (mm).

Snowmelt was computed by SWAT using a mass balance approach. First, the amount of snowmelt (mm of H_2O/day) was estimated by the following equation.

$$SNO = SNO + R_{day} - E_{sub} - SNO_{mlt} \quad (3)$$