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Catchment response to climate and land use changes in the Upper Blue Nile sub-basins, Ethiopia

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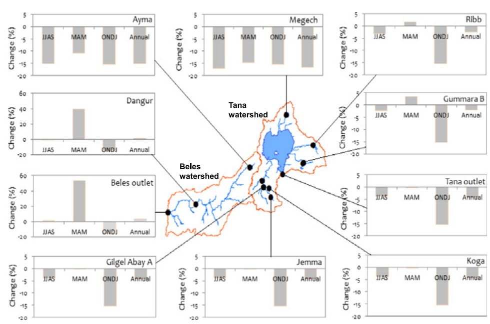
HIGHLIGHTS

- Climate in the study area is projected to be warmer and wetter in near-future.
- SWAT was used to assess the combined effects of climate and LULC change scenario.
- Climate scenario would intensify extreme flow in both sub-basins.
- LULC scenario might mitigate these extreme flows due to climate change.
- GCMs simulated rainfall underestimated historical rainfall during rainy season.

GRAPHICAL ABSTRACT



Changes in streamflow response to future land-use and land-cover (LULC) change scenario relative to that for 2010 LULC

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ABSTRACT

The impacts of climate and land development on streamflow and water balance components were analyzed in the Tana and Beles watersheds by using the Soil and Water Assessment Tool (SWAT). Streamflow response to simultaneous future land-use and land-cover (fLULC) and climate change (fCC) scenarios on the seasonal scale varied among the key water abstraction locations. The General Circulation Models (GCMs) average simulation of short-term climate indicated wetter and warmer climatic condition compared to that in the baseline period (1971/1980–2013). The near–future climate scenario would intensify extreme flow by increasing rainy season flow and reducing dry period flow. However, conversion of cultivation land on steep slope into forest might mitigate these extreme flows. At the outlet of Tana watershed, streamflow response would be amplified under concurrent scenarios of fLULC and fCC; but the streamflow would have an augmenting response at the outlet of the Beles watershed. Compared to response due to fCC alone, the streamflow and surface runoff components under combined fLULC and fCC scenarios would be alleviated in sub-catchments subject to conversion of cultivation in steep slope into forest land. The present results have significances for water resource management and land use planning in the Tana and Beles watersheds, and for other regions encountering identical pressures from climate change and LULC dynamics. In view of ongoing land use and climate dynamics, environmental policies must be carried out to cope with the potential changes of hydrologic regime. Moreover, catchment management should be adapted to changing hydrological regimes at different water abstraction points.

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1. Introduction

Land degradation as a threat to food security is a center of much attention globally, and particularly in developing countries, which rely on agricultural production for their economic growth and nations livelihood. Soil erosion by water is the dominant threat to 56% of the global area affected by soil degradation (Oldeman et al., 1994). Deforestation and over-exploitation of natural vegetative cover for domestic use are also the most causative factors for soil degradation. Soil degradation by erosion has both on-site and off-site effects (Tamene and Vlek, 2008). On-site effects of soil erosion imply nutrients loss, decline of rooting depth, and water storage capacity due to topsoil removal, and ultimately reduced land productivity. On the other hand off-site effects of soil erosion manifest in downstream flooding, sediment load in rivers, and reduction of storage capacity of dams due to siltation which ultimately affects energy generation and food production.

Climate, land-use and land-cover changes are among the main drivers of land degradation. It is especially aggravated if land-use and land-cover changes represent environmental land use conflicts, whereby the new use deviated from land capability (the natural use determined by soil characteristics and catchment parameters like slope, drainage density, etc.). In these cases, land degradation can be severely amplified (Pacheco et al., 2014). Climate change and variability effect land degradation by facilitating soil erosivity, especially that intensive rainfall accelerates soil erosion in bare vegetation cover. Runoff generation is a key process in land degradation, resulting in soil erosion and affecting the hydrological regime of the watersheds (Descheemaeker et al., 2006). Thus, understanding how climate change and land-use and land-cover (LULC) dynamics influence the variations in water resources/basin hydrology is vital for sustainable land and water resources management, which eventually reduce land degradation. Modeling studies (e.g. Tu, 2009; Kim et al., 2013; Wang et al., 2014; Fan and Shibata, 2015; Yin et al., 2017) on the combined influences of climate change and LULC dynamics have indicated that either change may be more considerable based on scenario assumptions and watershed characteristics.

In addition, the two types of changes may either augment or lessen the effects of one another on different spatio-temporal scales. The influence of climate change on catchment hydrology may result from spatio-temporal precipitation shifts, changes in evapotranspiration due to rises in temperature, and increase in extreme climatic events (Lahmer et al., 2001). Although less studied, the climate change impacts on catchment hydrology can even result in significant lowering of water table levels and base flows, with negative consequences for crop irrigation and groundwater supply to populations (Santos et al., 2014). Commonly, paired catchments, statistical analyses, and modeling approaches have recently been applied to know how climate change and LULC dynamics contribute to changes in water balance or basin hydrology. The paired catchment method is not applicable for large catchments due to unavailability of two similar large watersheds (Li et al., 2009). The statistical approach analyzes the hydroclimatic trends at monitoring stations (Bewket and Sterk, 2005); however, it fails to capture the physical processes in the watershed. In view of this, a spatially distributed hydrological model is considered as the most suitable method for determining the extent of influences of future climate combined with LULC changes. Physically based hydrological models have also been applied to quantify the relative effects of climate change and LULC on catchment hydrology (e.g. Schilling et al., 2008; Ma et al., 2009).

Many previous studies have examined the combined effect of climate and LULC changes on hydrology in different parts of the world (e.g. Tomer and Schilling, 2009; Tu, 2009). The outcomes of these studies (e.g. Choi, 2008; Kim et al., 2013) revealed that climate change was more dominant than LULC change in influencing the catchment hydrological regime. Due to the dissimilarity of the climatological and different physiographical conditions, climate and LULC change impact studies on water resources usually have a local to regional nature (Roosmalen et al., 2009).

One of those regions which reflect extensive LULC changes is the Upper Blue Nile Basin. As the economy of the region mainly depends on crop production, which in turn mainly depends on availability of water resources, the basin is very sensitive to rainfall-runoff generation. Crop cultivation by rainfall is the major source of food production in the study region, but its productivity is declining due to land degradation (Taddese, 2001). Small meteorological changes can lead to in comparatively large changes in the Blue Nile streamflow and water availability (Beyene et al., 2010). Besides, cultivation on steep slope coupled with intense rainfall might increase surface runoff, which in turn might accelerate land degradation. Streamflow response to environmental changes at key water abstraction points (currently operational, under-construction, and proposed water resource projects) in the watersheds is not well addressed. As the principal supplier to the Nile flow, the Tana and Beles watersheds (Fig. 1) response to environmental change (including LULC and climate change) is crucial for the Nile River flow in general, and the catchments in particular. However, previous studies in this region have usually focused on separate impacts of either climate change (e.g. Abdo et al., 2009; Beyene et al., 2010; Taye et al., 2011; Hadgu et al., 2015; Haile and Rientjes, 2015; Gebremedhin et al., 2017; Gizaw et al., 2017) or LULC change on hydrology (e.g., Rientjes et al., 2011; Tekleab et al., 2014; Welde and Gebremariam, 2017). Having separate studies of LULC or climate changes does not completely answer the questions as to the resulting influences on water resources. It is, therefore, crucial to consider both climate change and LULC dynamics and to evaluate their relative influence to hydrologic change.

The objectives of this study are: 1) to examine the response of hydrological processes to LULC and/or climate changes at the Tana and Beles watersheds; 2) to differentiate the impacts of LULC and/or climate changes on streamflow and hydrological components at key water abstraction points and watershed outlets. Since General Circulation Models (GCMs) are the key sources of projected climatic data applied to assess the effects of climate change on catchment water balance, this study utilizes aggregated GCMs outputs from the fifth Assessment Report (AR5) of the IPCC. AR5 adopted new scenarios, known as representative concentration pathways (RCPs), depending on different technical progresses. The RCPs are a group of greenhouse gas concentration and emissions pathways formed to provide interactive approach to climate change studies (Moss et al., 2010; Van Vuuren et al., 2011). RCP 6.0 is an intermediate pathway in which radiative forcing is maintained at approximately 6 W/m^2 after 2100.

2. Description of the study area

The Tana and Beles watersheds comprise the source of the Upper Blue Nile (Fig. 1). The two watersheds are joined through a Tana-Beles tunnel. There are three seasons in the study area: The main rainy season, which refers to the months June to September; the small rainy season that lasts from March to May; and the dry season, which lasts from October to February (NMA, 1996). The study region has been threatened by land degradation caused by deforestation, expansion of cultivation land, overgrazing and untenable use of land and water resources (Hurni, 1990). Expansion of cultivation into steeper lands and former forests provokes soil erosion and shortage of fuel wood. Crop cultivation by rainfall is the major source of food production in the study region. During the years when the rainfall is below average, crop yield reduction or total crop failure as well as power interruptions are common and have serious impact on food and energy security. Therefore, irrigation development and hydropower generation are considered a basis of the food and energy security in the study region. As a result, the government of Ethiopia has realized the importance of hydropower and small-scale irrigation projects (key water abstraction points in Fig. 1) and catchment management projects in the study area. The major LULC classes in the Tana sub-basin is cultivation land while that in the Beles sub-