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Hydrological responses to land use/cover changes in the source region of the Upper Blue Nile Basin, Ethiopia

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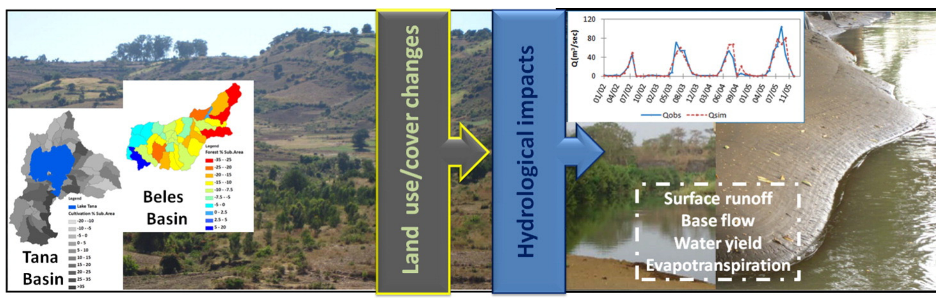
HIGHLIGHTS

- Contribution of the individual land use/land cover on hydrology is examined.
- Expansion rate of cultivation land in Tana sub-basin reduced recently.
- We examined how land use/cover changes affect the water balance at basin scale.
- Expansion of cultivated land increased surface runoff and decreased groundwater flow.
- Conversion of natural vegetation to cultivated land is the major environmental stressor.

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding how changes in distinctive land use/land cover (LULC) types influence the basin hydrology would greatly improve the predictability of the hydrological consequences of LULC dynamics for sustainable water resource management. As the main flow contributor to the River Nile, quantifying the effect of LULC change on water resources in the source regions is very important for the assessment of water resources availability and management downstream in the riparian states in general and the study watersheds in particular. In this study, an integrated approach comprising hydrological modeling and partial least squares regression (PLSR) was used to quantify the contributions of changes in individual LULC classes to changes in hydrological components. Two watersheds, namely Lake Tana and Beles in the Upper Blue Nile Basin in Ethiopia, were considered for the conduction of hydrological modeling using LULC maps and the Soil and Water Assessment Tool (SWAT). In the Tana sub-basin, it is found that expansion of cultivation land and decline in woody shrub are the major contributors to the rise in surface run-off and to the decline in the groundwater component. Similarly, decline of woodland and expansion of cultivation land are the major contributors to the increase in surface run-off and water yield in the Beles sub-basin. Increased run-off and reduced baseflow and actual evapotranspiration would have negative impacts on water resources, especially in relation to erosion and sedimentation in the upper Blue Nile River Basin. As a result, expansion of cultivation land and decline in woody shrub/woodland appear to be major environmental stressors affecting local water resources. The wider implications of the hydrological changes on the Easter Nile water resources are briefly discussed. The approach to assessing changes in basin hydrology could generally be applied to a variety of other watersheds for which temporal digital LULC maps are available.

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1. Introduction

Assessing the impacts of land use and land cover (LULC) changes on hydrology is vital for watershed management and development. Changes in LULC modify the rainfall path into run-off by altering critical hydrological components, such as surface run-off, groundwater recharge, infiltration, interception and evaporation (Costa et al., 2003; Mao and Cherkauer, 2009; Sajikumar and Remya, 2015). These LULC changes have potentially large impacts on the relations between rainfall and run-off; however, a greater challenge is to quantify these impacts for large basins, where the interaction between LULC, the climate characteristics and the underlying hydrological processes are complex and non-static (e.g. Uhlenbrook et al., 2003). Methods for assessing the hydrological impacts of LULC changes in river basins include hydrological modeling, multivariate statistics, and paired catchments (e.g. Zhang and Schilling, 2006; Bi et al., 2009; Khoi and Suetsugi, 2014). The use of a physically based distributed hydrological model is a common approach to assessing the impact of LULC changes on hydrology. This includes analysis of spatial hydrological responses to different LULC maps, comparison of basin scale average values of simulated hydrological components in response to LULC changes at the basin scale, and assessment of temporal responses in river discharge with changes in LULC (e.g. Hernandez et al., 2000; Miller et al., 2002; Niehoff et al., 2002; DeFries and Eshleman, 2004; Hundecha and Bardossy, 2004; Ghaffari et al., 2010; Nie et al., 2011; Yan et al., 2013; Gumindoga et al., 2014). Different watershed models such as AvGWLF (Tu, 2009), DHSVM (Cuo et al., 2008), PRMS (Qi et al., 2009), MIKE-SHE (Stoll et al., 2011), and SWAT (Hernandez et al., 2000; Miller et al., 2002; Ghaffari et al., 2010; Nie et al., 2011; Getachew and Melesse, 2012; Yan et al., 2013; El-Khoury et al., 2015; Niraula et al., 2015) have been used to assess the impact of LULC dynamics on hydrology.

Many studies have reported the impact of LULC changes on hydrology at different spatial and temporal scales (Hundecha and Bardossy, 2004; Wang et al., 2007; Zhang et al., 2010; Rientjes et al., 2011; Warburton et al., 2012; Gumindoga et al., 2014; Kalantari et al., 2014). In the headwater region of the Blue Nile, however, most studies do not quantify the contributions of change in individual LULC classes to different hydrological responses. When accurate quantification is lacking, the influence of changes in some LULC classes on hydrologic components is perhaps overestimated, undervalued, or even misunderstood (Nie et al., 2011). In addition, impacts of LULC on hydrology in the Tana and Beles watersheds are poorly documented. To address this deficiency, this study applies an integrated approach of hydrological modeling and partial least squares regression analysis to quantify the contribution of changes in each LULC class to changes in hydrological components in the Tana and Beles sub-basins.

There are still valid research questions as to how concurrent changes in several LULC classes, and changes in individual LULC classes, influence each hydrological component. The answers to these questions will improve the predictability of hydrological consequences of LULC changes, and are thus crucial for future LULC and/or water resource planning and management. In view of this, and as the Tana and Beles watersheds are the main source regions of the transboundary river (the Nile), the quantification of relevant LULC changes is vital.

Therefore, the objectives of this study are to evaluate the impacts of LULC changes on the hydrology, and to quantify the contribution of changes in individual LULCs to changes in the major hydrological components, using partial least squares regression by considering Tana and Beles watersheds as a case study.

2. The study area

The Tana and Beles watersheds constitute the headwater region of the Upper Blue Nile. They cover an area of around 15,000 km^2 and 13,900 km^2 respectively. Lake Tana is the largest freshwater body in Ethiopia, and is fed by four perennial rivers: Gilgel Abbay, Ribb, Megech and Gummara. The river network of the two watersheds is interconnected through a tunnel, which discharges into the Beles river, from Lake Tana to the Tana–Beles hydropower station. The highest elevation at the Tana watershed is higher than 4000 m a.s.l., whereas that of the Beles watershed is around 450 m a.s.l. in the outlet of the sub-basin (Fig. 1). This highly varied topography, together with rainfall variability, leads to different climatic zones within the watersheds. The variation of rainfall and temperature with altitude partly dictates the presence of certain vegetation cover and areas suitable for certain type of crops.

The climate of the study area is characterized by tropical climate and dominated by its high altitude. The climate is also governed by the movement of the Inter-Tropical Convergent Zone (ITCZ) (Conway, 2000; Mohamed et al., 2005). Three seasons occur in the watersheds: the main rainy season, the small rainy season, and the dry period. The hydrological year is characterized by three phases: the main rainy season that lasts from June to September, the dry period from October to

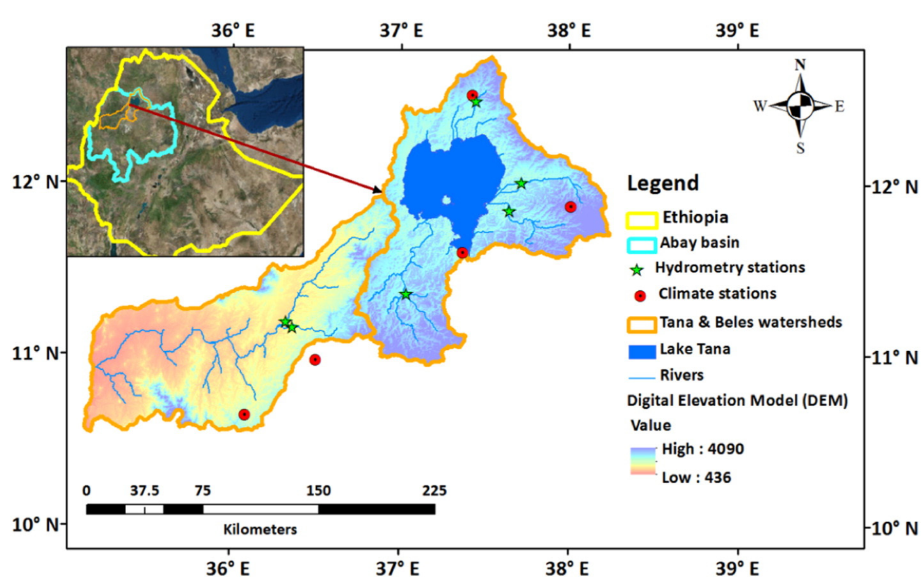

Fig. 1. Tana and Beles sub-basins.

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