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Evaluation of static and dynamic land use data for watershed hydrologic process simulation: A case study in Gummara watershed, Ethiopia

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ABSTRACT

Land Use Land Cover (LULC) change significantly affects hydrological processes. Several studies attempted to understand the effect of LULC change on biophysical processes; however, limited studies accounted dynamic nature of land use change. In this study, Soil and Water Assessment Tool (SWAT 2012) hydrological model and statistical analysis were applied to assess the impacts of land use change on hydrological responses such as surface runoff, evapotranspiration, and peak flow in Gummara watershed, Ethiopia. Moreover, the effects of static and dynamic land use data application on the SWAT model performance were evaluated. Two model setups, Static Land Use (SLU) and Dynamic Land Use (DLU), were studied to investigate the effects of accounting dynamic land use on hydrological responses. Both SLU and DLU model setups used the same meteorological, soil, and DEM data, but different land use. The SLU setup used the 1985 land use layer, whereas the DLU setup used 1985, 1995, 2005, and 2015 land use data. The calibration (validation) results showed that the model satisfactorily predicts temporal variation and peak streamflow with Nash Sutcliffe Efficiency (NSE) of 0.75 (0.71) and 0.73 (0.71) in the DLU and SLU setups, respectively. However, the DLU model setup simulated the detailed biophysical processes better during the calibration period. Both model setups equally predicted daily streamflow during the validation period. Better performance was obtained while applying the DLU model setup because of improved representation of the dynamic watershed characteristics such as curve number (CN2), overland Manning's (OV_N), and canopy storage (CANMX). Expansion of agricultural land use by 11.1% and the reduction of forest cover by 2.3% during the period from 1985 to 2015 increased the average annual surface runoff and peak flow by 11.6 mm and 2.4 m^3/s, respectively and decreased the evapotranspiration by 5.3 mm. On the other hand, expansion of shrubland by 1% decreased the surface runoff by 1.2 mm and increased the evapotranspiration by 1.1 mm. The results showed that accounting DLU into the SWAT model simulation leads to a more realistic representation of temporal land use changes, thereby improving the accuracy of temporal and spatial hydrological processes estimation.

1. Introduction

Land Use Land Cover (LULC) change is one of the major global environmental challenges to humanity. It significantly affected hydrological response (Wagner et al., 2016; Su et al., 2015), ecosystem services (Lawler et al., 2014), and climate processes. Memarian et al. (2014) and Gebremicael et al. (2013) showed that the expansion of agriculture land use causes a significant change in runoff and sediment load. Significant variation of evapotranspiration has occurred due to LULC and leaf area index change (Li et al., 2015). Land use change can lead to a significant change in groundwater recharge and base flow (Budiyanto et al., 2015), flood frequency and interval (Alexakis et al., 2014), peak runoff (Ahn et al., 2014), and total suspended sediment and nutrient concentration (Hwang et al., 2016). Moreover, the land use change affects local, regional and global climate system (Deng et al., 2013) and degrades the health of a wetland ecosystem (Alam et al., 2011). Land use change has been one of the main contributors to climate changes (Cao et al., 2015). On the other hand, climate change has also been affecting the land use system through changes in agricultural productivity and forest ecosystem (Wang et al., 2013).

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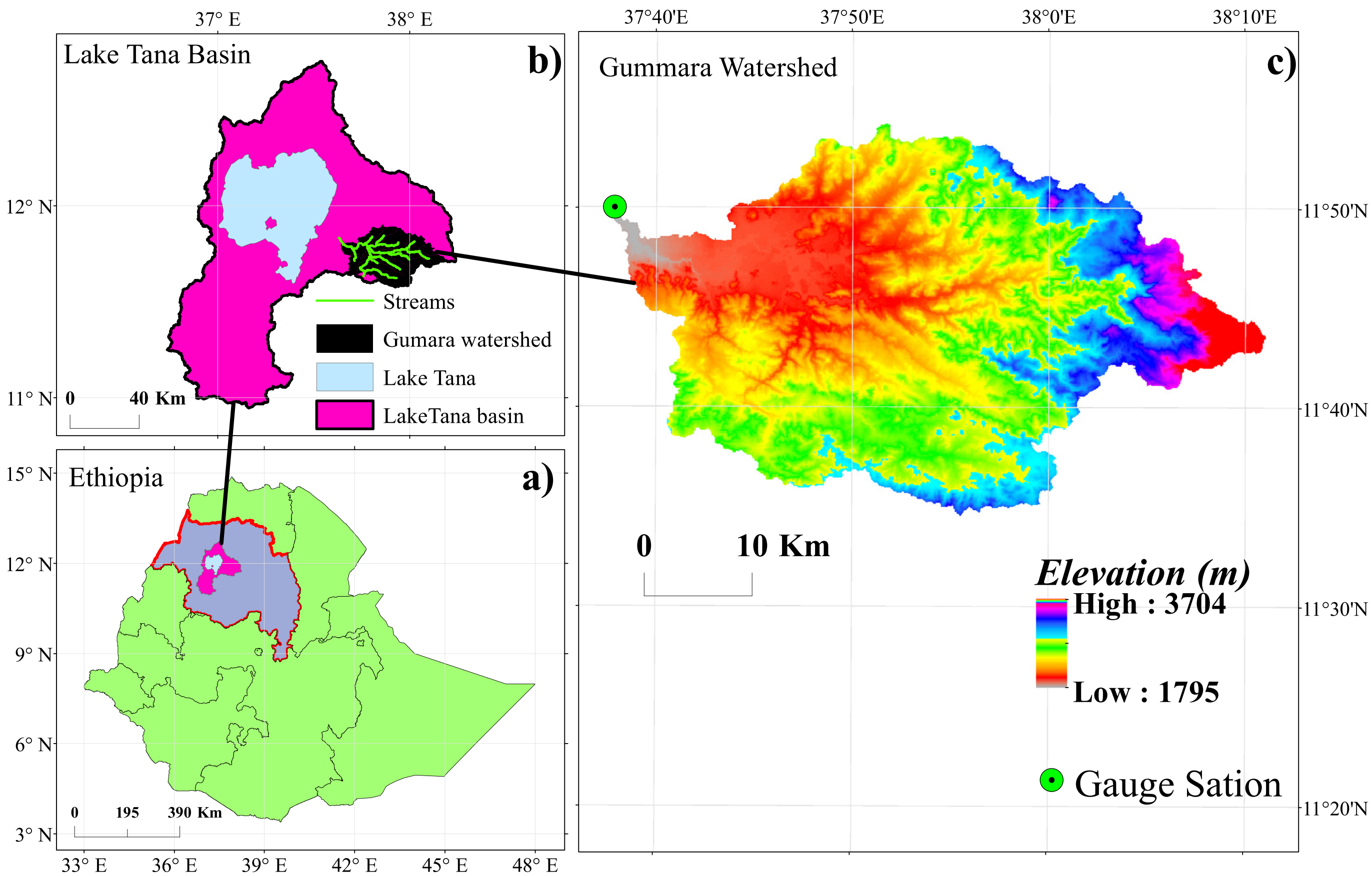

Fig. 1. Study watershed in the Lake Tana basin and Ethiopia. a) The location of the study watershed in the Amhara region (red border) and Ethiopia. b) Lake Tana basin showing the Gummera watershed in black border, and c) Gummara watershed zoomed with the elevation data as background.

Remote Sensing (RS), Geographic Information System (GIS), and hydrological modeling played a significant role in assessing the impact of land use change on different biophysical processes. RS data have played a major role in the watershed hydrological investigation (Ahn et al., 2014). LULC information derived from RS data has been used in a variety of hydrological modeling studies, especially in streamflow, water balance, flood event and soil erosion simulations (e.g., Dang and Kumar, 2017; Du et al., 2012). The GIS technology provided suitable alternatives for efficient management of large and complex databases. It also enhanced modeling efficiency and capability (Alexakis et al., 2014). For example, integration of the Soil and Water Assessment Tool (SWAT) with the GIS helped to understand the impacts of spatially explicit processes such as land use change on the hydrological response (Abbas et al., 2015; Yalew et al., 2013). Such tools have become vital for integrated river basin planning and management.

The SWAT model has strong track-record of evaluating the impacts of different land management practices on water budget, nutrient quantity and transport, and soil erosion in complex watersheds with varying soils, land uses, and management conditions over a long period of time (Arnold et al., 2012). For example, Briones et al. (2016) calibrated and validated SWAT model to study the impact of land use change on total water yields, groundwater, and base flow at sub-basin level in the Palico watershed in Batangas, Philippines. They showed that the combined forest and rangeland expansion by 22% increased base flow by 1–15%, and reduced streamflow by 1–17% in the rainy seasons. On the other hand, the reduction of forest cover by 54% decreased base flow between 11% and 17% in the rainy season, and increased surface runoff by 4–24%. Likewise, Huang and Lo (2015) applied the SWAT model to study the impacts of land use change on water budget and sediment losses over Yang Ming Shan National Park Watershed in northern Taiwan, and they reported that the conversion of forest land into agricultural land increased sediment loss.

Most SWAT model applications have been exclusively using static land cover data to study the effects of LULC change on watershed hydrologic modeling. Watershed processes represented by static land use data inadequately estimate the temporal and spatial hydrological variation (Wagner et al., 2016). Perhaps, use of dynamic land use (DLU) data may improve the spatial and temporal model simulation performance by capturing better the LULC evolution. Moreover, the DLU approach help to disaggregate the effects of land use change, climate variability and land management practices on the hydrological response (Fang et al., 2013; Chiang et al., 2010). Pai and Saraswat (2011) highlighted that stationarity in hydrological responses might happen in a single LULC application since such an approach simplifies the land use changes with time. Stationarity of hydrological responses can be resolved by integrating Land Use Change (LUC) modules into hydrological modeling approaches (Chiang et al., 2010; Saraswat et al., 2010). For example, Wagner et al. (2016) integrated SLEUTH land use change and the SWAT model, and they found sound seasonal and gradual changes in the water balance estimates. Similarly, Pai and Saraswat (2011), using LUC module with the SWAT model, improved the accuracy of estimation of the spatial and temporal hydrological fluxes such as surface runoff, groundwater, and evapotranspiration. However, several of these integrated LUC studies have the limitation of relying solely on model parameters derived from the calibration period, which uses static land use data. This approach overlooks the effects of land use changes on certain model parameters. For example, the study conducted by Gebremicael et al. (2013) showed there is a clear high discrepancy of calibrated model parameters between the 1973 and 2000 land use data for the 1971–1973 and 2000–2002 simulation periods, respectively. Since Gebremicael et al. (2013) uses different land use and climate data, the source of model parameter variation was