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Climatic controls of ecohydrological responses in the highlands of northern Ethiopia

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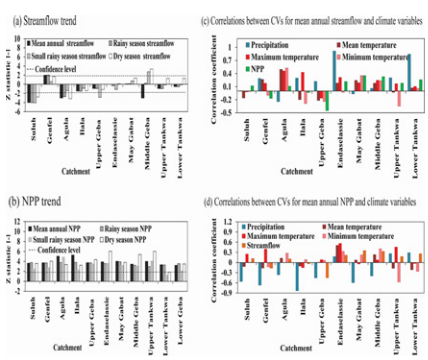
HIGHLIGHTS

- Trends and relationships of climatic variables, streamflow and NPP were examined.
- Streamflow trends are different in different sub-catchment at different time-scale.
- NPP exhibits significant positive inter-annual and seasonal trends.
- Precipitation and maximum temperature were the more dominant climatic variables.
- Human intervention has a profound effect on streamflow and NPP variation.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate variability and recurrent droughts have a strong negative impact on agricultural production and hydrology in the highlands northern Ethiopia. Since the 1980s, numerous mitigation and land rehabilitation measures have been implemented by local and national authorities to reduce these impacts, are often poorly effective. As underlying reason may be that controlling relationships between climate and ecohydrology at medium-sized catchments (10–10,000 km^2) of semi-arid highlands are not well known. We investigated trends and relationships in precipitation, temperature, streamflow, and net primary productivity (NPP). The results were mixed, with both significant increasing and decreasing trends for temperature and streamflow. Precipitation time series did not show a significant trend for the majority of stations, both over the years and over each season, except for a few stations. A time series indicated a significant abrupt increase of NPP in annual, seasonal and monthly timescale. Cross-correlation and regression analysis indicate precipitation and maximum temperature were the dominant climatic variables in the Geba catchment for streamflow and NPP. In view of these results, also land use and land cover change over the past three decades was analysed as a possible factor of importance, as human intervention, may affect streamflow and NPP. Factors that mainly correlate with streamflow and NPP are precipitation and maximum temperature. Important interventions that appear beneficial for these responses are construction of micro-dams, soil and water conservation and ecological restoration measures. The awareness that interactions can be quite different in semi-arid and semi-humid regions, as well as in upstream and downstream areas, should be reflected in management aimed at sustainable water and land resources use.

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1. Introduction

Ecohydrological processes are strongly determined by climate, primarily by precipitation patterns, air temperature and radiation (Canadell et al., 2006). The impacts of each factor to ecohydrology, however, differ depending on coupling and feedbacks between subsystems at many scales of space and time. Understanding of interactions and feedbacks between ecohydrological processes and climate is crucial for preparing effective strategies for upcoming challenges of society (Melesse et al., 2014; Sykes et al., 1999). Ideally, such understanding is supported by long term data and therefore trends, and variability of streamflow, ecosystem productivity, and climate have been investigated and related for diverse regions of the world (Hao et al., 2016; Peng et al., 2015; Jones et al., 2012; Potter et al., 2012; Witte et al., 2012; Twine and Kucharik, 2009; Dettinger and Diaz, 2000). The effects of precipitation and air temperature on ecohydrological responses, such as streamflow and ecosystem productivity, are not clear (Jones et al., 2012; Zhao and Running, 2010), perhaps because of the complexity of ecohydrological systems and human intervention.

The northern Ethiopian highlands are characterized by rugged topography, intense rainfall, and a sparse vegetation cover (Vanmaercke et al., 2010; Nyssen et al., 2004; Feoli et al., 2002). Therefore, climate variability and recurrent droughts have strong negative impacts on agricultural production and hydrology (Nyssen et al., 2004; Shanko and Camberlin, 1998). The amount and temporal distribution of rainfall is generally the most important determinant of inter-annual fluctuations in crop production in Ethiopia (Bewket and Conway, 2007; Araya and Stroosnijder, 2011; Conway and Schipper, 2011). Both Segele and Lamb (2005) and Araya and Stroosnijder (2011) provided evidence that frequent dry spells of about 10 days length are among the major causes of crop failure in rain-fed farming systems of Ethiopia. Araya and Stroosnijder (2011), for instance, mention that 40% of crop failure around Mekelle Airport station, in northern Ethiopia is due to dry spells during the growing season.

Drought struck Ethiopia in 1888, leading to the historic deadly famine of 1888/89 (Pankhurst, 1985). The 1957/58 drought and its related impacts led to famine in Tigray province and the 1972/73 famine caused by drought claimed 200,000 lives in Wollo province, northern Ethiopia. Although the drought in 1983/84 triggered a famine that lead to an estimated one million fatalities, less serious, nonetheless significant droughts, occurred in the years 1987, 1988, 1991–92, 1993–94, 1999, and 2002/3 in northern Ethiopia (Edossa et al., 2010). The severe drought of 2010/11 in eastern Ethiopia, Kenya and Somali, for example, affected some ten million people and was a contributing factor to >250,000 fatalities in Somalia alone (Checchi and Robinson, 2013). In the most recent drought (2015/16), about 10.2 millions of people have been affected in Ethiopia (FEWS NET, 2016).

Since the 1980s, numerous mitigation and land rehabilitation measures, such as terraces, stone bunds, construction of micro-dams, exclosures, and reforestation programmes, have been introduced to reduce adverse effects of climate variability and climate change in northern Ethiopia (Alemayehu et al., 2009; Descheemaeker et al., 2006; Haregeweyn et al., 2005). However, most of the implemented schemes are not sufficiently effective (Gebreyohannes et al., 2013; D. Teka et al., 2013; Haregeweyn et al., 2006). In 1994, the regional government of Tigray established a Commission for Sustainable Agriculture and Environmental Rehabilitation in Tigray (COSAERT) to construct 500 microdams within ten years to promote water harvesting and irrigation (Haregeweyn et al., 2006). After ten years, in 2003, only 54 dams had been built because of different practical problems such as insufficient inflow, sedimentation, evaporation, excessive seepage, and lack of appropriate dam sites (D. Teka et al., 2013; Berhane et al., 2012; Haregeweyn et al., 2006; Nyssen et al., 2004). Possibly, these problems are attributed to knowledge of the factors controlling the relationships and lack of reliable data during the planning, design, construction and post construction stages. For sustainable resource management, the processes and their spatiotemporal variability needs to be known (Conway et al., 2004), which is one incentive to aim for long data records for northern Ethiopian highlands.

The hydrological and ecological responses to climate change and human activity in the northern Ethiopian have been studied (Taye et al., 2013; Zenebe et al., 2013; Nyssen et al., 2010; Gebresamuel et al., 2009), but considered only short periods. Climate change (Gebreselassie and Moges, 2015; Hadgu et al., 2015; Tekleab et al., 2013), runoff, and streamflow generation (Ashenafi, 2014; Goitom, 2012; Zenebe et al., 2013) have been investigated, and much attention has been given to changes in land use and land cover (LULC) and to the restoration of vegetation (Haregeweyn et al., 2015; Descheemaeker et al., 2006; Hurni et al., 2005).

There are only a few studies on trends and relationships of climate and ecohydrological responses in northern Ethiopian highlands (Liu et al., 2008; Taye and Willems, 2012; Tekleab et al., 2013). These studies are either at national or basin scales which mask local scale variability. Liu et al. (2008) studied the rainfall-runoff relationships for the monsoonal climate, for the period (1945–1984) at three watersheds of the northern Ethiopian highlands: Andit Tid, Anjeni, and Maybar. They reported that all three watersheds exhibit consistent hydrologic behaviour after approximately 500 mm of cumulative effective seasonal rainfall since the beginning of season. Tekleab et al. (2013) investigated trends of precipitation, temperature, and streamflow over the Upper Blue Nile basin, for the period 1954–2008. They reported significant increasing trends in temperature, no statistically significant trends in precipitation, and both statistically significant increasing and decreasing streamflow trends in seasonal and extreme flow.

Taye and Willems (2012) studied temporal variability of hydroclimatic extremes in the Blue Nile basin using historical data (1964–2009). They showed that the high flow extremes of the Blue Nile are strongly influenced by climatic oscillations while the low flows are influenced by the combined effects of climate and land use and land cover changes. Similar studies also reported that the rainfall in the Ethiopian highlands during the rainy season has teleconnected to the ENSO phenomena (Camberlin, 1997; Conway, 2000). Seleshi and Zanke (2004) reported a cool tropical Indian Ocean can be associated to reduced rainfall conditions over the semi-arid lowlands of northeastern, eastern, southern, and southwestern Ethiopia. Nyssen et al. (2005) and Eklundh and Pilesjö (1990) also described the geographical or topographical factors, such as slope aspect, general orientation of the valley and slope gradient over longer distances, but not elevation, contributed to the spatial variability in precipitation in the northern Ethiopian highlands. Krauer (1988) mentions that the daily rain pattern in the Tigray region, where this study is conducted, is dominated by afternoon rains (with 47% of rain falling between 12 and 18 PM) provoked locally by the convective nature of the rains after heating of the earth surface in the morning.

To the best of our knowledge, only one study is available on the relationships between climate variables and net primary productivity (NPP) by Teferi (2015), in northern Ethiopian highlands. Teferi (2015) studied the patterns and climatic controls of vegetated land cover dynamics in Blue Nile (Abay) basin using satellite based estimates of NPP and water use efficiency (1982–2006). His results show significant positive correlation between NPP, rainfall and temperature in the humid zones, and significant negative correlation between NPP, maximum temperature and vapour pressure deficit in semi-arid zones of the study region. Interesting is that they found correlations between NPP and rainfall, which were marginal in the sub-humid zone, yet significant in the humid and semi-arid zones of the study basin. This suggests a sensitive dependence of interactions on (sub-)climate region.

Previous research conducted in the northern Ethiopian highlands has not resulted in sufficient understanding as needed for effective water and land management, particularly for the driest part of the semi-arid highlands of northern Ethiopia. Since previous studies focused more on humid climatic conditions (Teferi, 2015; Tekleab et al., 2013; Taye and Willems, 2012; Tessema and Lamb, 2003), or larger basin or national