Climatic controls of ecohydrological responses in the highlands of northern Ethiopia

Tesfaye, S., Birhane, E., Leijnse, T., & van der Zee, S. E. A. T. M.

Climatic Controls of Ecohydrological Responses in the Highlands of Northern Ethiopia

Samuale Tesfaye [a,b], Emiru Birhane [b,c], Toon Leijnse [a], SEATM van der Zee [a,d]

[a] Soil Physics and Land Management Group, P.O. Box 47, 6700 AA, Wageningen University, The Netherlands
[b] Department of Land Resources Management and Environmental Protection, Mekelle University, Ethiopia
[c] Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, No-1432 Ås, Norway
[d] School of Chemistry, Monash University, Melbourne, VIC 3800, Australia

---

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 (10–10,000km^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 analyzed as a possible factor of importance, as human interventions, 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 soil and water conservation, construction of micro-dams, 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.

Keywords: Precipitation, Streamflow, Primary Productivity, Ecosystem Model, Land Use, Semi-arid

---

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, differs 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 a 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 more than 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 programs, 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 (Geberyohannes et al., 2013; Teka D., 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 micro-dams 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 (Teka D., 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, 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., 2013; Tekleab et al., 2013), runoff, and streamflow generation (Ashenafi, 2014; Goitom et al., 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 (Hargeweyn 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, 1995; 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 et al. (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 to 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 et al., 2010), or larger basin or national scales (Liu et al., 2008; Hurni, 2005; Gete and Hurni, 2001), local conditions may have been misrepresented. Our aim, therefore, is to identify and characterize trends, change points, and cross-correlations of precipitation, temperature, streamflow, and NPP. Rather than previous work at either larger scales or more humid conditions, this investigation focusses at the medium-sized catchment scale (10–10,000 km^2) in the semi-arid highlands of northern Ethiopia, where recent interventions have not been as successful as needed.

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 et al., 2010), or larger basin or national scales (Liu et al., 2008; Hurni, 2005; Gete and Hurni, 2001), local conditions may have been misrepresented. Our aim, therefore, is to identify and characterize trends, change points, and cross-correlations of precipitation, temperature, streamflow, and NPP. Rather than previous work at either larger scales or more humid conditions, this investigation focusses at the medium-sized catchment scale (10–10,000 km2) in the semi-arid highlands of northern Ethiopia, where recent interventions have not been as successful as needed.

2. Material and methods

2.1. Study site

The study area, the upper Tekeze (Atbara) basin of Geba catchment in the Tigray region of northern Ethiopia, extends from 13°18′00″ to 14°15′00″N and from 38°37′48″ to 39°47′24″E (Fig. 1). It covers an area of 5142 km^2, and the elevation ranges from 914 to 3316 m a.s.l., with a mean of 2145 m (± 641). The highest point is in the northeast of the catchment. Eleven sub-catchments of the Geba catchment were studied (Appendix A, Table A.1). Suluh (SU), Genfel (GE), Agula (AG), Ilala (IL), and May Anbesa (MA) are found in the upper region of the catchment. May Gabat (MG), Endaselassie (ES), and Bershwa (BS) are sub-catchments of the middle region of the catchment. Upper Tankwa (UT), Lower Tankwa (LT) and Chemay (CH) are located in the lower region of the catchment (see Fig. 1 and Appendix A, Table A.1).

The topography of the Geba catchment is highly controlled by erosional features and geological structures. Sharp cliffs and steep slopes border the major rivers. Slope gradient range from 1.5 to 26.7%, with a mean of 15.2%. The catchment has a semi-arid climate, with a season of heavy rains (June to September), a smaller rainy season with less rain (March to May), and a dry season (October to February). The mean annual rainfall for 1980–2014 ranged from 552 to 767 mm. The temperature is rather uniform throughout the year except for diurnal variations. The mean annual temperature ranges from 16 to 20 °C. The mean annual potential evapotranspiration is 1688 mm, with a maximum of 2538 mm in the west part of the lower region and a minimum of 905 mm in the central highlands of the upper region of the catchment (Gebreyohannes et al., 2013). The Geba catchment is characterised by a mixture of land use and land cover (LULC).

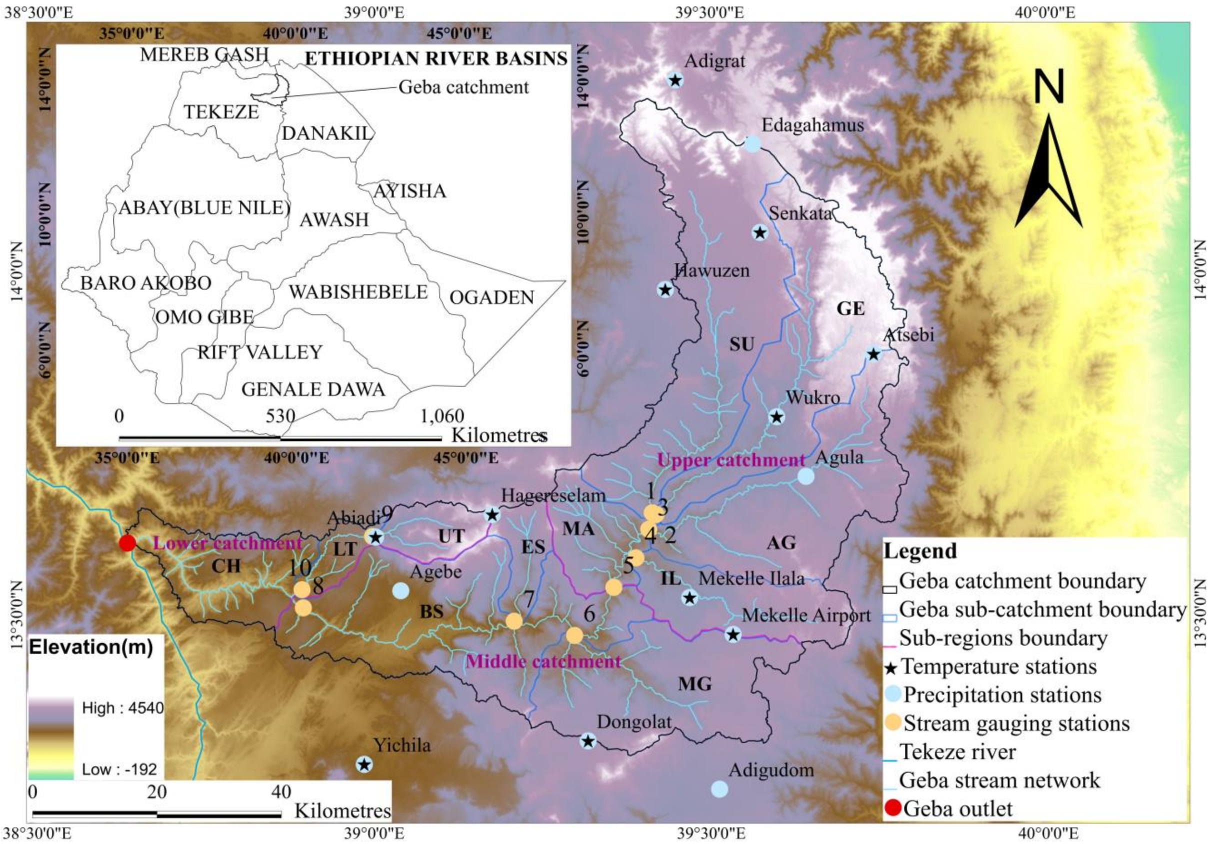

Fig. 1. Map of the study area, illustrating the regions (purple line) and sub-catchments (blue line), location of streamflow and meteorological stations, and the catchment topography. Geba catchment outlet is marked with a red dot. The numbers of the streamflow gauging stations and abbreviation identifying the sub-catchments are provided in Appendix A, Table A.1.

The area consists of crop land (45.6%), shrub covered areas (29.9%), grass land (8.7%), bare soil (7.95%), artificial surfaces (4.9%), tree covered areas (2.8%), and water bodies (0.15%) (own processing from 2014 Landsat images). The dominant soil types are Eutric Leptosols, Vertic Cambisols, Rendzic Leptosols, Chromic Luvisols, and Calcic Vertisols (FAO, 1998; Tielens, 2012).

2.2. Data collection and processing

Satellite images, streamflow and climatic variables were used as data sources. Remote sensing and geographic information system techniques were used for processing, analysing, and mapping all spatial data. Mann-Kendall (Mann, 1945; Kendall, 1975) and Pettitt (Pettitt, 1979) tests were used to analyse the trends and change points, respectively. Pearson correlation coefficients, and cross-correlation analysis were also used to investigate the relationships between streamflow, NPP, precipitation and temperature.

2.2.1. Satellite data

Three types of data sets were used: (1) Global Inventory, Monitoring, and Modelling Studies (GIMMS) 15-day composite normalised difference vegetation index (NDVI) data, (2) Moderate-resolution Imaging Spectroradiometer (MODIS) 16-day L3 Global 250 m NDVI (MOD13Q1) data, and (3) Landsat TM images (April, 1984; and March, 1995; 2003) and ETM Plus satellite images (February, 2014). The GIMMS NDVI data product (Tucker et al., 2005) was used to analyse long-term (1982–2000) NPP trends and variability in the catchment. The MOD13Q1 NDVI datasets used to investigate NPP for 2001–2014 were extracted from the NASA (National Aeronautics and Space Administration) Land Processes Distributed Active Archive Centre (LPDAAC, https://lpdaac.usgs.gov/dataset_discovery/modis/modis_ products _table/mod13q1). Land use and land cover (LULC) data from the Landsat images with a spatial resolution of 30 meters (interpreted from Landsat TM and ETM Plus images) is used to determine the LULC change, and fraction of photosynthetically active radiation and the maximal light-use efficiency (LUE) to input into the CASA (Carnegie-Ames-Stanford Approach) model. Land use and land cover maps were developed and grouped according to the FAO Global Land Cover SHARE classes (FAO, 2014) into 7 land use and land cover types: (1) tree covered areas; (2) shrub covered areas; (3) grass land; (4) artificial surfaces; (5) crop land; (6) bare soil and (7) water bodies.

2.2.2. Climatic and streamflow data

Daily and monthly series of precipitation data for 15 stations and temperature data for 10 stations were obtained from the Ethiopian National Meteorological Agency (Appendix A, Table A.2). Data for monthly total solar radiation at a spatial resolution of 0.5×0.5° for input into the CASA model was obtained from a data set reanalysed by the National Centre for Environmental Prediction (NCEP) DOE-II (Zhao and Running, 2010). Streamflow data for 10 gauging stations in the catchment periods of different duration were obtained from the Ethiopia Ministry of Water Resources, Irrigation and Energy and the MU-IUC/VLIR-UOS (interuniversity collaboration between the Flemish universities and Mekelle university) programme archive (see Appendix A, Table A.1). The data set for streamflow and climatic variables was scanty, with much missing data (see Appendix A, Table A.1 and 2). To get monthly mean precipitation, temperature, and streamflow, the missing values at stations were filled through statistical regression analysis, using loading factors estimated from the coefficients of correlation between stations (Yang et al., 2010). This was achieved by establishing the linear, power, logarithmic and exponential cross-correlation equations between the observed variables at stations which have missed values and those at other stations for each month of the year. Missing monthly variable values then calculated at each station using the best performing equation and corresponding variable data observed at the other station. Each climatic variable in and around the catchment was processed by using Thiessen polygon to acquire the interpolated value for the sub-catchments.

2.3. Data analysis

The Mann-Kendall test was used to assess trends in precipitation, temperature, streamflow, and NPP. We used trend-free pre-whitening (TFPW) to remove the auto-correlation before executing the trend analysis, as descried by Yue et al. (2003). Pettitt tests were used to identify change points in the time series. Trends and change points were evaluated for 1980–2014. Trends magnitude was computed for assessing the rate of change per unit time as proposed by Sen (1968) (Appendix B, B.3). We used the improved CASA model (Yu et al., 2009) for estimating monthly NPP (presented in Section 2.4). Pearson's correlation coefficients were determined for the correlations between streamflow, NPP, and climatic variables (precipitation, mean temperature, maximum temperature, and minimum temperature). It was assumed that the inter-annual (seasonal and monthly) fluctuation of streamflow and NPP could be attributed to the temporal and spatial variability of these climatic variables when the correlations between the coefficients of variation (CVs) for streamflow, NPP, and climatic variables were significant (Gong et al., 2012). The method of time-lagged cross-correlation analysis (Appendix C) was used to study the immediate and delayed effects of climate variables on monthly variations of streamflow and NPP, as described by Fik and Mulligan (1998), and Peng et al. (2008).

2.4. The CASA ecosystem model

The CASA ecosystem model based on estimating light-use efficiency (LUE) is a process-based model appropriate for estimating NPP on global or regional scales (Potter et al., 1993; 2009; Yu et al., 2009). The product of absorbed photosynthetically active radiation (APAR) and LUE was used to define NPP (Potter et al., 1993):

$$NPP_{(x,t)} = APAR_{(x,t)} \times LUE_{(x,t)} \quad (1)$$

where $APAR_{(x,t)}$ (MJ/m^2/month) and $LUE_{(x,t)}$ (g C/MJ) are the APAR and LUE of the vegetation in the geographic coordinate system at location x and time t.

The algorithm for APAR is given by (Piao et al., 2001):

$$APAR_{(x,t)} = SOL_{(x,t)} \times FPAR_{(x,t)} \times r \quad (2)$$

where $SOL_{(x,t)}$ (MJ/m^2/month) and $FPAR_{(x,t)}$ are the monthly total solar radiation and the fraction of the incoming photosynthetically active radiation intercepted by green vegetation at position x and time t, and *r* is the ratio of the photosynthetically active radiation (PAR) (with a wavelength range of 0.4–0.7 mm) that can be used by the vegetation with the incoming solar radiation ($r \approx 0.5$) (Gong et al., 2012).

Eq. (2) indicates that APAR depends on FPAR and PAR. FPAR is mainly determined by vegetation type and its canopy. The normalised difference vegetation index (NDVI), calculated from remotely sensed data, assesses the vegetation canopy (Potter et al., 1993). FPAR is linearly correlated with NDVI (Yu et al., 2009; Potter et al., 1993):

$$FPAR(x,t) = \frac{[NDVI(x,t) - NDVI_{i,min}] \times (F_{max} - F_{min})}{NDVI_{i,max} - NDVI_{i,min}} + F_{min} \quad (3)$$

where $F_{min} = 0.001$ and $F_{max} = 0.95$ are the minimal and maximal FPAR, respectively, and are independent of vegetation type, and $NDVI_{i,min}$ and $NDVI_{i,max}$ are the minimal and maximal NDVI values of vegetation type i and represent bare ground and complete coverage, respectively.

LUE is the basis for the CASA model, and the algorithm can be expressed by:

$$LUE(x,t) = T_{\varepsilon1(x,t)} \times T_{\varepsilon2\,(x,t)} \times W_{(x,t)} \times \varepsilon\,max \quad (4)$$

where $T_{\varepsilon1(x,t)}$ and $T_{\varepsilon2\,(x,t)}$ are temperature-stress coefficients, $W_{(x,t)}$ is the moisture-stress coefficient, and $\varepsilon\,max$ is the maximal LUE of the vegetation in ideal conditions. The algorithms for $T_{\varepsilon1(x,t)}$ and $T_{\varepsilon2\,(x,t)}$, and the improved $W_{(x,t)}$ have been described by Potter et al. (1993) and Yu et al. (2009). The model uses the regional moisture index (the ratio of regional actual evapotranspiration with potential evapotranspiration) which is computed from monthly climate data, to estimate the influence of moisture-stress coefficient ($W_{(x,t)}$) on light-use efficiency. Details about this model are described by Yue et al. (2009). The maximum LUE (ε max) was set uniformly at 0.55 gC/MJ PAR, estimated globally from field measurements by Potter et al. (2003).

3. Results and discussion

3.1. Trends and change-point detection

3.1.1. Precipitation and temperature

The precipitation and temperature records between 1980–2014 are shown in Appendix A (Table A.2). The Mann-Kendall method was used to investigate the trends at the annual, seasonal and monthly time scales. In Fig. 2A, total annual precipitation tended to decrease at about 60% of the stations. For the seasonal cases, the trends in the rainy season showed a decrease for about 47% of the stations. Similarly, precipitation decreased at about 40 and 47% of the stations in the small rainy and dry seasons, respectively. These decreasing trends are found to be statistically significant (<0.5 level of significance) and comprise of a reduction of 13% of precipitation for the annual and small rainy season, and 27% for dry season.

The magnitudes of the significant decreasing trends at Edega Hamus and Hawzen in the upper region of the catchment respectively, are, in mm/year per year: -9.33 and -4.87 in annual, -3.56 and -1.67 in small rainy season, and -0.45 and -1.1 in dry season. Hager Slam in small rainy season, Wukro and Mekelle Airport in dry season also showed significant decreasing trends of precipitation by -1.55, -0.38, and -0.49 mm/season per year, respectively. In contrast Abi Adi in the lower region, and Dengolat in the middle region revealed a significant increasing trends of precipitation in rainy season by 30.81 and 7.04 mm/season per year, respectively (Fig. 2E).

According to the performed analysis, the test result for the monthly scale precipitation in February and May at seven and two stations, respectively, showed a statistically significant decreasing trend mainly in the upper region of the catchment. August and September precipitation also showed a mixture of statistically significant decreasing trends in the upper, and increasing trends in the lower regions of the catchment stations. For 73.3% of the stations, change point analysis of precipitation showed no abrupt changes for either total annual or seasonal precipitation. Precipitation in small rainy season had a downward shift at Edega Hamus station in 1996, Hawuzen station in 1997, and Hager Slam station in 1997. For 53.3% of the stations, an abrupt change was observed in the monthly precipitation, with a significant change in February precipitation over the past 35 years (not shown). Depending on the station, time scale and sub-season, both decreasing and increasing trends have been observed. However, significantly decreasing trends are mainly observed in the northern part of the upper region (Edega Hamus, Hawzen, Wukro and Mekelle Airport), and middle region (Hager Slam) of the catchment, while stations in the middle region (Dengolat) and lower region (Abi Adi) showed significant increasing trends. Perhaps, the spatial difference in magnitude and direction across the catchment, e.g., the two nearby stations, Hager Slam and Abi Adi, which showed the significant decreasing and increasing trends, respectively, attributed to the difference in topographical factors between the two stations (Nyssen et al., 2005).

The results are in agreement with those previously reported in the other parts of the country (e.g., Beyen, 2015; Tabari et al., 2015; Viste et al., 2012). Tekleab et al. (2013) found a mixture of positive and negative trends in total annual, seasonal, and daily precipitation in the Blue Nile/Abay basin for the period 1954–2008. However, some previous rainfall trend studies have reported a declining trend of annual and seasonal rainfall in north central and central Ethiopia (FEWS, 2003; Osman and Sauerborn, 2002; Seleshi and Dameree, 1995), and no significant trend in northeastern, northwestern and central parts of the country (Conway, 2000; Meze-Hausken, 2004; Seleshi and Zanke, 2004, Seleshi and Camberlin, 2006). This difference may come from the use of climatic data from different time spans or moments chosen for the analysis (Bewket and Conway, 2007).

A decadal analysis by McSweeney et al. (2008) reveals that annual precipitation decreased during the 1980s in many parts of Ethiopia, and recovered during the early 1990s and late 2000s, with the exception of 2002–2003 when the country experienced a severe drought period. However, when the analyzed period is made larger, this decreasing trend in annual rainfall is reduced or even removed. Seasonal and intra-seasonal trends may exist, as may more localized trends (Seleshi and Camberlin, 2006). Similarly, the annual precipitation in this study showed decreasing trends in the 1980s, an annual normal to slightly above the average trend in the years 1990s, decreasing and then increasing trends in the years 2000s, and slightly reduced trend in the 2010s at the majority of stations (Appendix D, Fig. D.1).

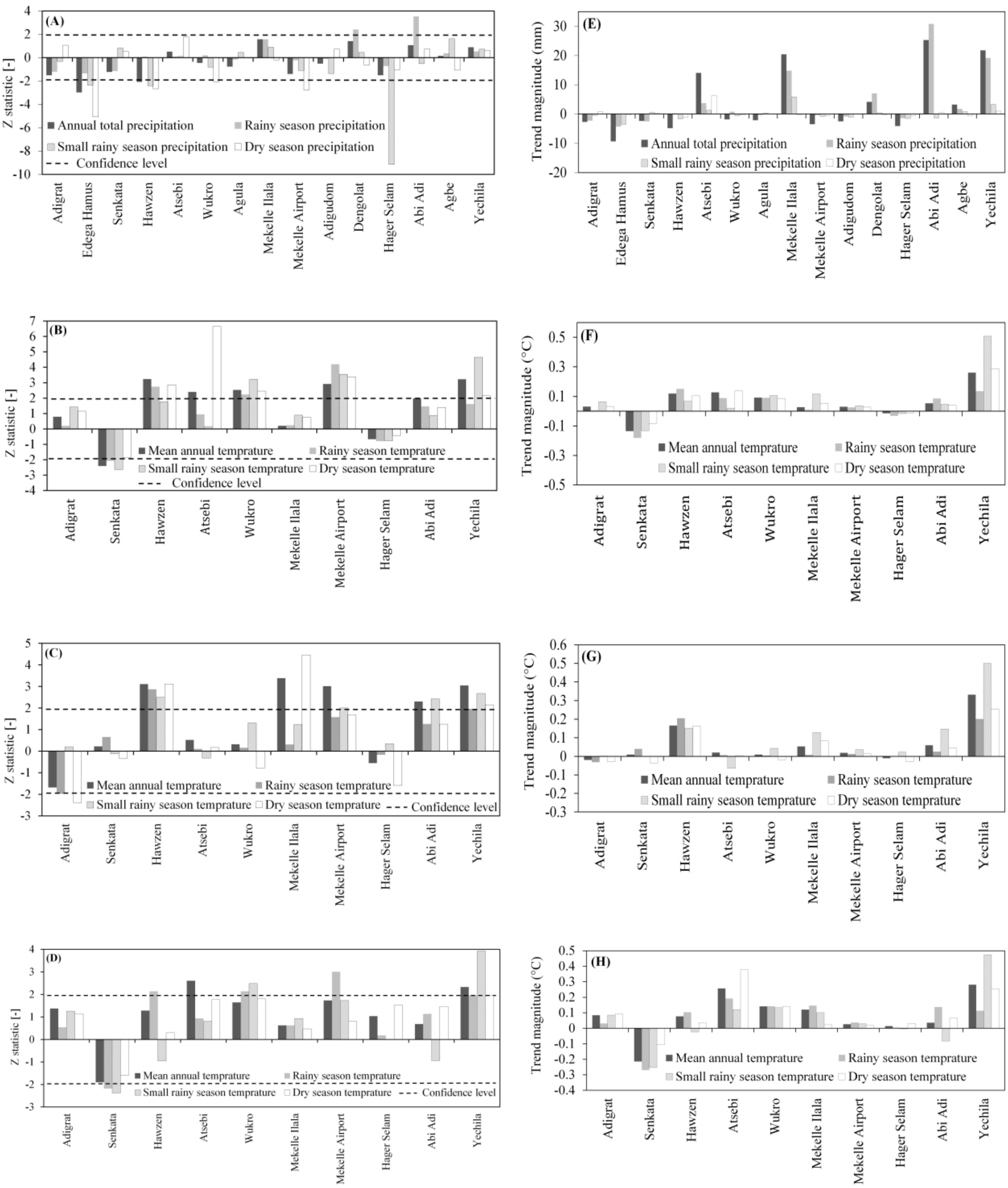

Fig. 2. Mann-Kendall test Z statistics and trend magnitudes for annual and seasonal trends in precipitation and temperature at the Geba catchment climatic stations. Graphs in the left row represent the Mann-Kendall test Z statistics for total annual precipitation (A), monthly mean of daily mean temperature (B), monthly mean of daily maximum temperature (C), and monthly mean of daily minimum temperature (D); Graphs in the right row represent the trend magnitudes for total annual precipitation (E), monthly mean of daily mean temperature (F), monthly mean of daily maximum temperature (G), and monthly mean of daily minimum temperature (H).

From Fig. 2B, C and D, it is evident that the annual and seasonal daily mean, maximum, and minimum temperatures tend to strongly increase at the majority of the stations. Monthly means of daily mean temperatures in the annual, rainy season, small rainy season, and dry season increased significantly (<0.5 level of significance) for 60, 30, 30, and 50% of the stations, respectively. Annual means of daily maximum temperatures increased significantly for 50% of the stations for annual temperature and 20, 40, and 30% of the stations for the rainy, small rainy, and dry seasons, respectively. However, the stations found in the northern part of the upper catchment showed negative trends in minimum, and maximum temperatures (e.g., Adigrat and Senkata).

The trends of mean annual minimum temperature indicated a warming in most regions of the catchment (90% of the observed stations), with significant increases in the upper region of the catchment (Atsebi station) and near the middle region of the catchment (Yechila station). Minimum temperature also showed significant increasing trends during rainy seasons at Hawuzen, Wukro, Mekelle Airport stations in the upper region and Yichela station in the middle region, as well as at Wukro station during small rainy season, and Yichila station during small rainy and dry seasons. The highest rate of increase was found for the small rainy season (0.24 °C/y) and, not surprisingly, the lowest rate of increase for the dry season (0.186 °C/y). At one station, i.e., at the Senkata station in the northern region of the Geba catchment, annual and seasonal daily mean and minimum temperatures, tended to decrease.

The analysis of the Pettitt test allows us to confirm the results obtained previously, and to locate the years of change (Appendix A, Table A.3). Change points differed between the stations and cannot well be compared to those of other studies due to different lengths of the data records. The change points differed for the stations, and for instance, for Adigrat and Mekelle Airport even for the data set concerning the same period (1980–2014). The change points at Adigrat station occurred in 2011, 1991, and 1987, while at Mekelle Airport station, the changes occurred in 1996, 1996, and 1989, for mean, maximum, and minimum temperatures, respectively.

Figure 2F, G and H shows the magnitudes of trends in the annual mean, maximum and minimum temperatures, respectively at annual and seasonal time scales. The increase in annual mean, maximum and minimum temperatures among stations ranged from 0.26–0.84 °C, 0.04–1.09 °C and 0.13–1.64 °C per decade, respectively. At the seasonal scale, similar increasing trends among stations ranged from, 0.2–1.23 °C, 0.06–3.27 °C and 0.22–1.75 °C per decade in mean temperature, 0.01–1.44 °C, 0.02–2.71 °C and 0.03–2.0 °C per decade in maximum temperature, and 0.13–1.79 °C, 0.01–3.24 °C and 0.24–1.80 °C per decade in minimum temperature were observed for main rainy, small rainy and dry seasons, respectively. The trends of temperature were not uniform across stations. Significant warming trends were observed at Hawuzen, Atsebi, Wukro and Mekelle Airport in upper region, Yichela in middle region, and Abi Adi in lower region of the catchment, with respect to annual mean temperature. In contrast, at Senkata station in the upper region significant cooling trend was experienced by -1.3 °C/decade. The annual mean temperature increased by 1.2, 1.3, 0.9 and 0.3 °C/decade for Hawuzen, Atsebi, Wukro and Mekelle Airport stations in upper region of the catchment, respectively, nearly by twofold faster than the country's average warming rate of 0.37 °C per decade for 1951–2006 (NMA, 2007) and sixfold faster than the global average warming rate of 0.12 °C/decade (0.72 °C increase for 1951–2012; IPCC, 2013).

Our results are in line with previous studies with climate change in Ethiopia, which reported increasing temperature trends (e.g. Hadgu et al., 2015; Beyen, 2015). NMA (2007) reported that between 1960–2006, the mean annual temperature has increased at an average rate of 0.2 °C per decade over Ethiopia. A warming trend at a rate of 0.25 °C per decade for 1952–1999, whereas NMA (2007) reported an increase of 0.37 °C per decade for 1951–2006. Gebrehiwot and van der Veen (2013) also indicated an increase in both mean minimum and maximum temperatures for 1954–2008 of 0.72 and 0.36 °C/decade, respectively in the northern Ethiopia. Conway et al. (2004) found a warming trend in the annual mean maximum and minimum temperatures by 0.2 °C and 0.4 °C per decade for Addis Ababa for 1951–2002. In general, rates of change appear to differ between areas and time periods studied, but most studies concur on the presence of a warming trend in Ethiopia in both the mean, maximum and minimum temperatures over the past few decades. The increase in temperature particularly during the small rainy and rainy seasons at the majority of the stations impose its impact on the onset period of crop production by raising the evaporative demand, particularly in the upper and middle regions where a decline of precipitation amount is observed. Beside a reduced length of the growing period, seasonal rainfall with high evaporative demand will increase the risks of low yields in rain-fed crop production.

3.1.2. Streamflow

For all investigated periods of annual and all seasons except the dry season, more stations showed a decreasing trend of monthly mean streamflow (Appendix A, Table A.4). The stations with significant negative trends of annual and seasonal streamflow are mainly found in the upper region of the catchment. In the upper region of the catchment, streamflow tended to decrease significantly at Suluh and Agula stations, and increased significantly at Genfel station during annual and main rainy season. Streamflow also showed significant decreasing trends for Suluh and Upper Geba stations during small rainy and dry seasons, and for Agula station during the small rainy season. To some extent, the hydrological stations showed a decreasing trend agree with the pattern of meteorological stations with significant negative trends in precipitation (refer to Fig. 2).

Comparison between the sub-catchments, however, was not possible due to limited data availability for the catchment. Different stations and for different periods revealed different trends. For instance, Appendix A (Table A.4), and Fig. 3 illustrate that streamflow tended to decrease significantly in the upper region at the Upper Geba station in the small rainy season, and at the Suluh station in the annual and all seasons streamflow. Annual, rainy and dry seasons streamflow, however, increased significantly at the Genfel station, which is adjacent to the Suluh station. The most likely reason for this difference is the presence of micro-dams and diversions in the Genfel catchment, which create a smoothing effect in runoff distribution and limit the detection of changes at the gauging station. Moreover, water abstractions for irrigation and seasonal distribution of rainfall, which can be attributed to the change in streamflow, differ between the sub-catchments. Water-harvesting structures, river diversions, and more than 54 micro-dams have been built in the Tigray region since 1992; 28 of these were large- or medium-sized (3.1 to 0.1 $10^6 m^3$) micro-dams in the Geba catchment (Haregeweyn et al., 2008; Yazew et al., 2005), which have decreased runoff and hindered the detection of changes at the gauging stations. Tekleab et al. (2013) also reported a mixture of increasing and decreasing trends in the Blue Nile/Abby basin caused by human intervention.

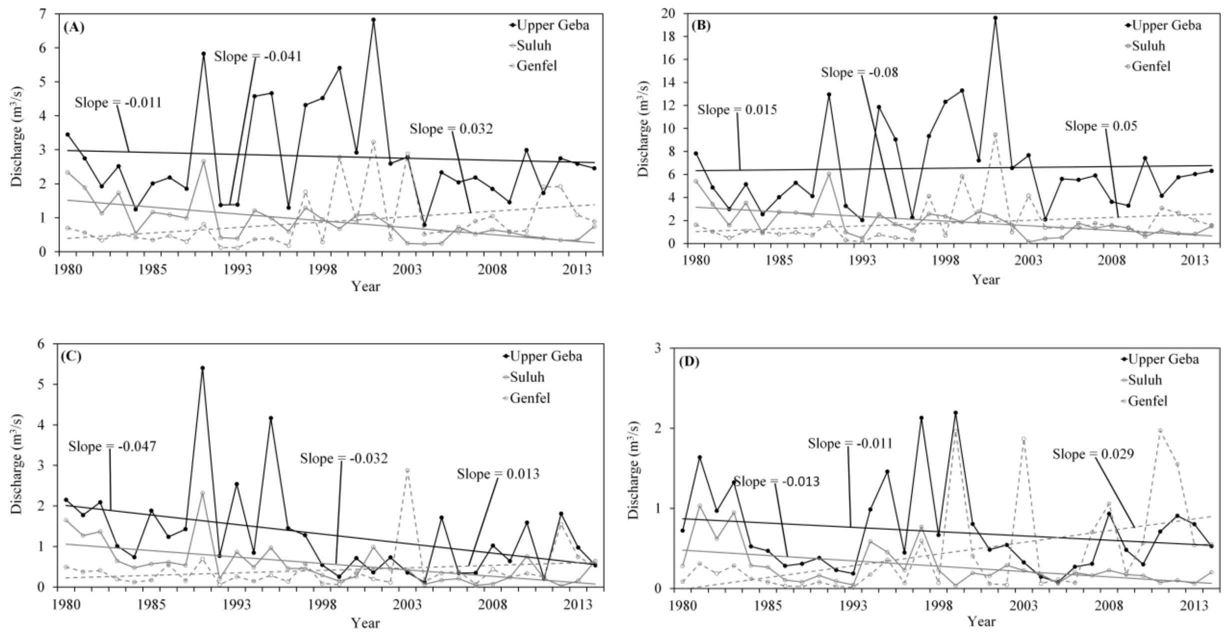

Fig. 3. Time-series plots for mean annual discharge (A), rainy season mean discharge (B), small rainy season mean discharge (C), and dry season mean discharge (D) at the Upper Geba, Suluh, and Genfel gauging stations in the upper region of Geba catchment.

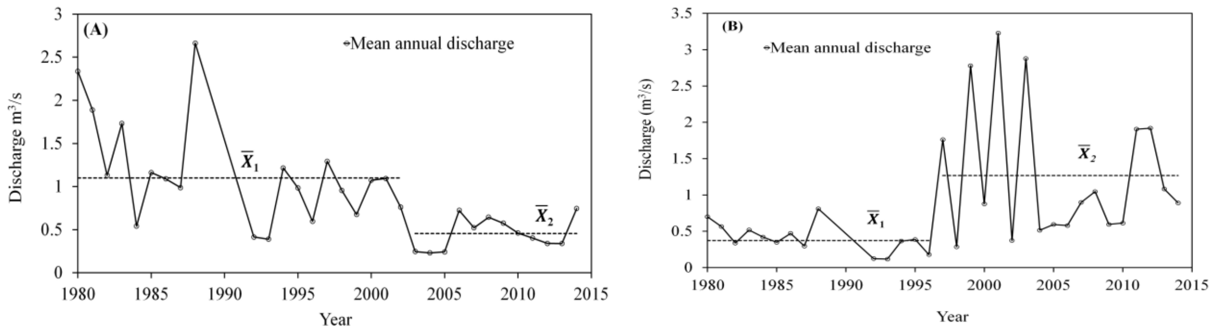

Fig. 4. Time-series plots for the changes in mean annual discharge at the Suluh sub-catchment (A) and Genfel sub-catchment (B) gauging stations. The dashed lines labelled $\overline{x}_1$ and $\overline{x}_2$ are the means of the time series before and after the change points, respectively.

The break points of the annual mean streamflow are shown in Appendix A, Table A.5. Significant downward shifts were generally detected for annual mean streamflow at most of the stations. The time-series plots for the changes in annual mean streamflow for the representative stations, Suluh and Genfel stations are presented in Fig. 4. Streamflow decline in Suluh started as early as 1988. It has accelerated since 1996 and the trend became significant after 2002. For Genfel station, an upward shift of streamflow started as early as 1987 and the trend became significant after 1996. This pattern can also be largely attributed to the operation of the micro-dam reservoir since 1992, and to the 1990–92 and 1999–2000 droughts in the region (Edossa et al., 2010). The upward shifts were likely due to the implementation of large-scale measures for conserving soil and water in the sub-catchment since 1980s (Asfaw, 2014; Nyssen et al., 2010). The impact of human activities as land rehabilitation measures, and land use and land cover change, on streamflow is discussed in a later Section 3.2.3.

3.1.4. NPP

The spatiotemporal changes of NPP are summarised in Appendix A (Table A.4). The monthly mean annual NPP increased significantly in the Geba catchment. The average annual

NPP and inter-annual variation for 1982–2014 were 1.64 gC/m^2 and 0.71 gC/m^2, respectively (Appendix D, Fig. D.2). Based on the Theil-Sen slope trend (see Appendix C, Fig. C.1 C), the catchment showed a positive trend in monthly mean annual NPP with a mean rate of 0.068 NPP units (3.9% per year).

Annual and rainy season NPP increased markedly in the Agula and Ilala sub-catchments of the upper region of Geba catchment. Endaselassie sub-catchment in the middle and Upper Tankwa sub-catchment in the lower regions also had similar tendencies for the small rainy and dry seasons. These similar results may be primarily the results of increased vegetation coverage through ecological restoration measures, such as exclosure and reforestation (Nyssen et al., 2015; Teka K et al., 2013; Gebersamuel et al., 2010). For example, annual and seasonal NPP increased significantly at the representative sub-catchments of Suluh, Bershwa, and Chemay in the upper, middle, and lower regions of the catchment, respectively (Fig. 5). The monthly NPP also showed a strong increase in all sub-catchments. Average annual NPP was highest in the upper region (1.69 gC/m^2) among the three region of Geba catchment which is covered by Afromontane forest in the eastern and southern parts (mainly in the escarpments of Agula, Ilala and Genfel sub-catchments) of the region (see Appendix D, Fig. D.2, and Appendix E, Fig. E.1).

The average annual NPP in the sub-catchments was highest in the Upper Tankwa (2.03 gC/m^2), followed by Endaselassie (1.78 gC/m^2) from the 11 sub-catchments, where the vegetation is dominated by shrubs and deciduous forests (TECSULT, 2004; 2014 LULC, own processing). NPP was next highest in the Agula (1.68 gC/m^2) and Genfel (1.61 gC/m^2) sub-catchments, which contain reforestation and patches of escarpment forest (Zeneb, 2009; TECSULT, 2004), followed by the Ilala sub-catchment (1.60 gC/m^2) in the southern parts of the upper region of Geba catchment. NPP was lower in the Suluh sub-catchment (1.57 gC/m^2)

in the upper, May Gabat sub-catchment (1.56 gC/m^2) in the middle, and Lower Tankwa sub-catchment (1.49 gC/m^2) in the lower regions of the Geba catchment.

The Pettitt tests identified several change points for the 11 Geba sub-catchments (Appendix A, Table A.5), and illustrated in Fig. 6 for the two representative sub-catchments. Mean annual NPP shifted upward in all sub-catchments around 2000. Upward shifts were significant in all seasons. Change points of monthly mean annual NPP in the small rainy and dry seasons occurred around 1994 and 1995 in the Suluh and Genfel sub-catchments, respectively. Upward shifts in the rainy seasons for these sub-catchments occurred around 2000. Most change points were upward shifts in monthly NPP. The upward change points for all sub-catchments occurred mostly around the early 1990s and 2000s.

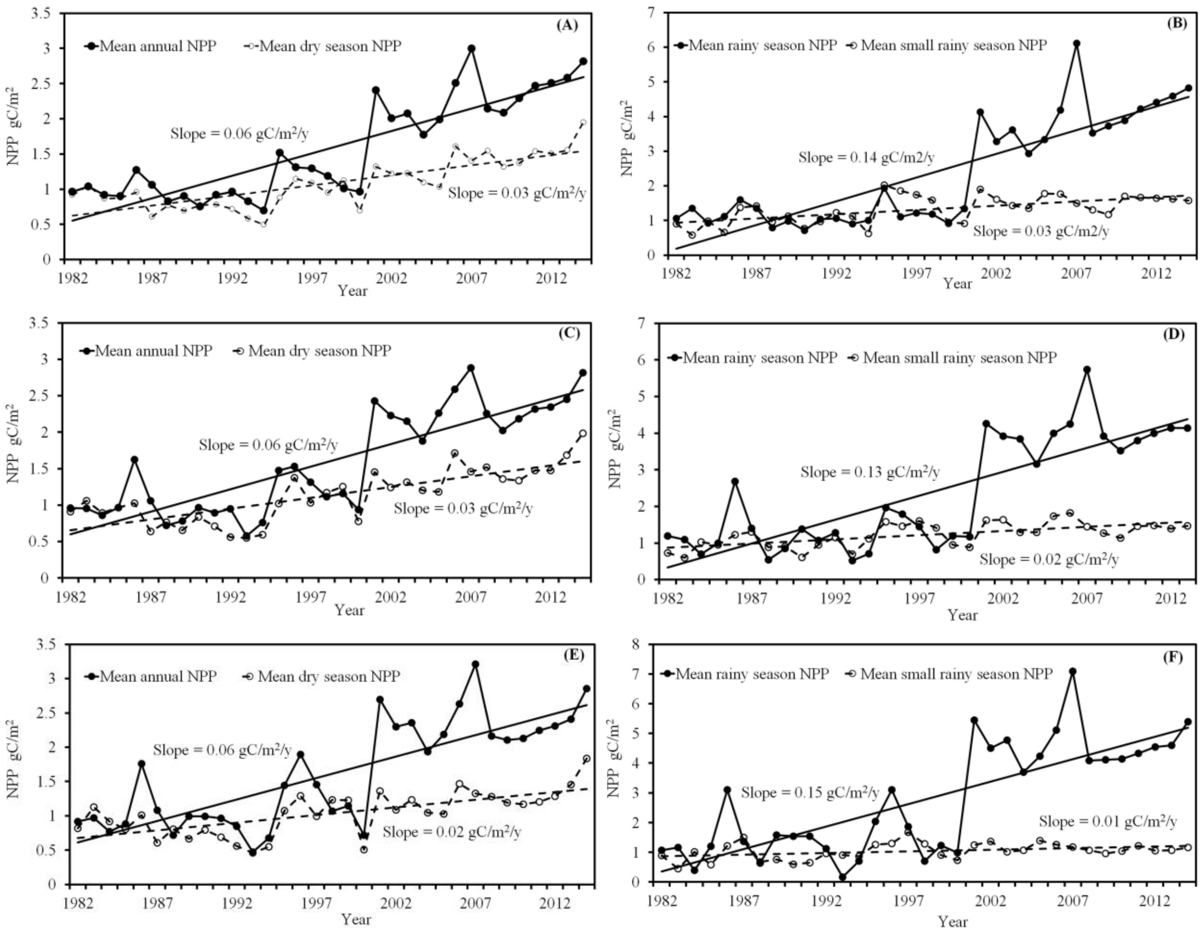

Fig. 5. Time-series plots of NPP for the Suluh (A and B), Bershwa (C and D), and Chemay (E and F) sub-catchments in the upper, middle, and lower regions of the Geba catchment, respectively.

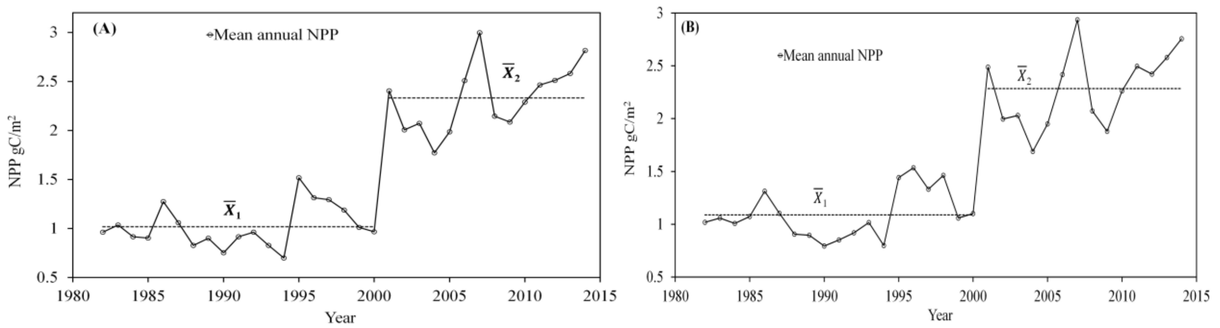

Fig. 6. Time-series plots for the NPP change points for the Suluh (A) and Genfel (B) sub-catchments. The dashed lines labelled $\overline{X}_1$ and $\overline{X}_2$ are the means of the time series before and after the change points, respectively.

The results from our study showed an increase of temperature and a decrease of precipitation in some parts of the catchment, and overall increase of NPP in the region, a similar result as also obtained elsewhere by Huntingford et al. (2000) and Mohammed et al. (2004). These results are difficult to explain as simply a combined effect of the semi-arid ecosystem. The following mechanism, however, may provide an explanation for the changes of NPP.

Increase of minimum temperature in rainy and small rainy seasons, and decrease of precipitation in small and dry seasons are mostly found in the upper region of the catchment. This finding may be due to the fact that the upper region of the catchment is found in high altitude areas and have lower temperature, that increase in rainy and small rainy season minimum temperature advances an upward trend as a result (Zhang et al 2013; Zhao and Running, 2010). While a decrease of precipitation in small and dry seasons have moisture stress to some extent. As the small rainy and dry seasons contributed less amount of precipitation (less than 20%) to the annual average in the catchment. Moreover, mechanisms other than climate, such as CO_2 fertilization, and N deposition, may also play roles in the increasing of NPP trend (Jacob et al., 2015). Therefore, it is likely that the marked changes of the NPP seen in the upper region were mainly caused by human interventions, which will be discussed in Section 3.2.3.

3.2. Relationships of climate variables and human activities with ecohydrologic responses

Ecohydrologic responses, streamflow and NPP were dynamic at annual and seasonal time scales. The spatial and temporal variations of these changes reflect the combined effects of climate change and human activities, which provides valuable information in water and land resources management in the catchment. In this study, attempts, therefore, are made to investigate the relationships of streamflow and NPP with climate variables and human activities in the catchment.

3.2.1. Correlation between streamflow, NPP and climate

The correlation coefficients of the relationships between the mean values and CVs for streamflow, NPP, and climatic variables are shown in Appendix D (Fig. D.3), and Fig. 7, respectively. Mean annual and seasonal streamflow were correlated positively with mean precipitation, and negatively with mean and maximum temperatures. Mean minimum temperature was correlated negatively with mean annual and rainy season streamflow, and positively with mean small rainy and dry season streamflow in most parts of the catchment.

The CVs for annual and seasonal streamflow were correlated positively with precipitation, and with the CVs for mean and maximum temperatures (see Fig. 7). However, the CVs for streamflow and precipitation were negative correlations in some parts of the catchment. Correlation analysis between the CVs for annual and rainy season streamflow and minimum temperature showed negative relationships, whereas the CVs for small rainy and dry seasons streamflow were positively correlated with minimum temperature, in most regions of the catchment.

Streamflow reflects the integrated response of the entire river catchment on weather forcing, and on particularly precipitation. In this study, we detected a significant decreasing trend of streamflow, particularly on small rainy and dry seasons, at Upper Geba station which is located at the outlet of the upper region of the catchment river. A similar significant decreasing trend was observed for the upper region of the catchment precipitation, especially in May and February which are the small rainy and dry seasons months, respectively.

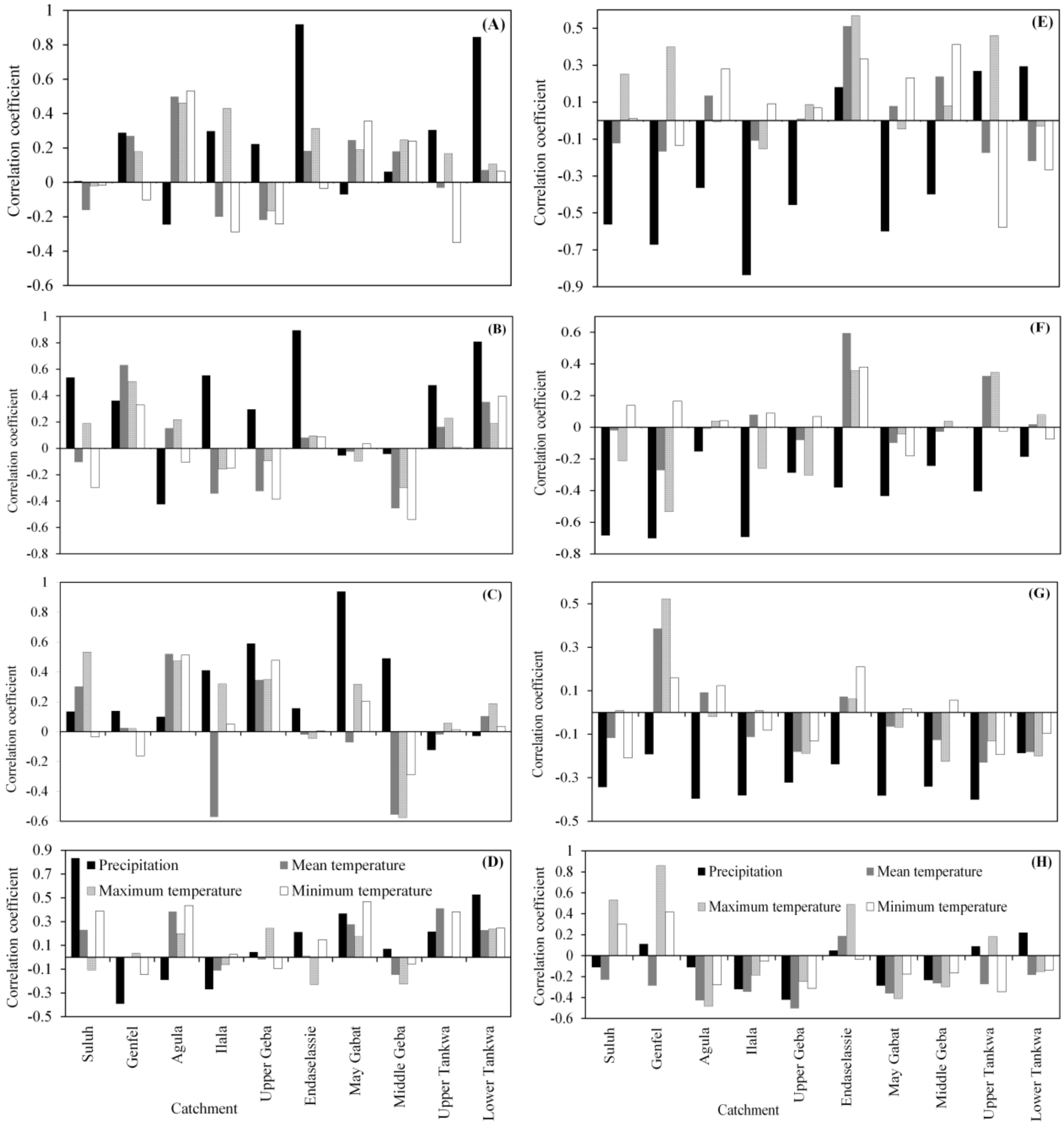

Fig. 7. Correlations between the CVs for mean annual, rainy season, small rainy season, and dry season streamflow and NPP, and the CVs for precipitation, mean temperature, maximum temperature, and minimum temperature at a seasonal time scale. Graphs in the left row represent the correlations between the CVs for mean annual (A), rainy season (B), small rainy season (C), and dry season (D) streamflow; Graphs in the right row represent the correlations between the CVs for mean annual (E), rainy season (F), small rainy season (G), and dry season (H) NPP.

Therefore, the decreasing trend of precipitation in the upper region of the catchment contributed to the decreasing streamflow. It is further evident by the significant correlation coefficient between CVs for streamflow and precipitation in the majority of the stations. The significant correlation indicates that the precipitation influences the streamflow directly. This observation is also supported by the close relationship observed by Zeneb et al. (2013) between runoff and precipitation in the Geba catchment for 2004–2007. The study by Taye et al. (2013) used a simple lumped rainfall–runoff models to identify the sources of observed temporal variability of hydrological extremes of the entire upper Blue Nile basin for 1964–2009. They reported that rainfall variability is the main influencing factor for the observed extreme flow pattern in the basin. However, the impacts of human intervention were not clearly considered since the models used are lumped rainfall-runoff models that did not consider such catchment heterogeneities. Hence, it is likely that the effect of climate variability on streamflow is mainly through the changes in precipitation. However, the changes in precipitation were small in this study.

Climatic variables controlling NPP also varied on many scales of space and time. No single climatic variable was correlated with annual and seasonal NPP in the sub-catchments. Mean annual and seasonal NPP were correlated positively with mean precipitation, and negatively with mean temperature and maximum temperature (Appendix D, Fig. D.4). Mean annual and rainy season NPP were negatively correlated with mean minimum temperature. For the mean small rainy and dry season NPP, the relationship was less evident as they were for some cases negatively and others positively correlated with mean minimum temperature in the catchment. Whereas means of NPP were positively correlated with precipitation, the CVs for annual and seasonal NPP were negatively correlated with the CVs for precipitation in most of the sub-catchments (see Fig. 7). The CVs for annual and rainy season NPP were either positively or negatively correlated with the CVs for mean temperature, and the CVs for small rainy and dry season NPP were negatively correlated with the CVs for mean temperature in most parts of the catchment. The CVs for annual and rainy season NPP were positively correlated with the CVs of maximum and minimum temperatures, and the CVs for small rainy and dry season NPP were negatively correlated with the CVs for maximum and minimum temperatures in the catchment.

The CVs for annual and rainy season precipitation, and the CVs for rainy and dry seasons maximum temperature were significantly correlated with CVs for the respective NPP, where the correlation with precipitation is higher than that for maximum temperature. The significant correlations of mean values and CVs for NPP and climate factors as precipitation and maximum temperature reveal their impact and role in the inter-annual and seasonal variation of NPP in the catchment. That the inter-annual and seasonal variation of NPP can be attributed mainly to precipitation and maximum temperature is remarkable, considering the relatively small fluctuation of both precipitation and maximum temperature. Teferi (2015) also reported a 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. His results also show NPP and rainfall are correlated marginally in sub-humid zones.

From the above analysis, we learn that the annual, seasonal, and monthly changes of precipitation, mean temperature, maximum temperature, and minimum temperature all contributed to the inter- and intra-annual fluctuation of streamflow and NPP. However, precipitation and maximum temperature were important influencing climatic factor in the Geba catchment. Climatic variations have also been associated with long-term regional droughts identified by pollen analysis (i.e. vegetation coverage) (Lanckriet et al., 2015). The impact of the different climatic variables differed for different regions and may be related with LULC and the agro-climatic zonation (Teferi et al., 2015; Tekelab et al., 2013; Zenebe et al., 2013; Nyssen et al., 2005).

3.2.2. Time-lagged correlation between streamflow, NPP and Climate

Results of lagged correlation analysis between monthly streamflow and NPP, and precipitation, mean temperature, maximum temperature and minimum temperature are shown in Fig. 8. The analysis shows that streamflow is well correlated with precipitation across the catchment. It is found that almost for all the months streamflow with precipitation correlation decreased with an increase in time-lag. Significant positive zero and one months lagged correlations between streamflow and precipitation were observed. For the study catchment, the correlation between streamflow and temperature are found to be poorly correlated and highly variable for all the years. No consistent change in correlation between streamflow and temperature was found with increase in time-lag. 20 and 40% of the sub-catchments streamflow showed a significant negative one month lagged correlation, and positive two months lagged correlation with mean temperature, respectively. Streamflow for most of the sub-catchments had a significant negative zero lagged correlation to maximum temperature, and significant positive zero and one month lagged correlation to minimum temperature.

The lower and middle regions of sub-catchment streamflow are strongly correlated with precipitation at zero lag with compared to the upper region of sub-catchments. While in the upper region, sub-catchments showed strong correlation between streamflow and precipitation at one month lag than the lower and middle regions sub-catchment (see Fig. 8). The significant positive correlations between streamflow and precipitation indicates that the streamflow is much more sensitive to precipitation and that the dependence increases from upstream to downstream in most of the sub-catchments. The relationships also suggested that sub-catchments in the lower and middle regions are respond more strongly to changes in precipitation than sub-catchments in upper region. However, the magnitude of the changes in streamflow depends on both changes in precipitation and human intervention in the regions.

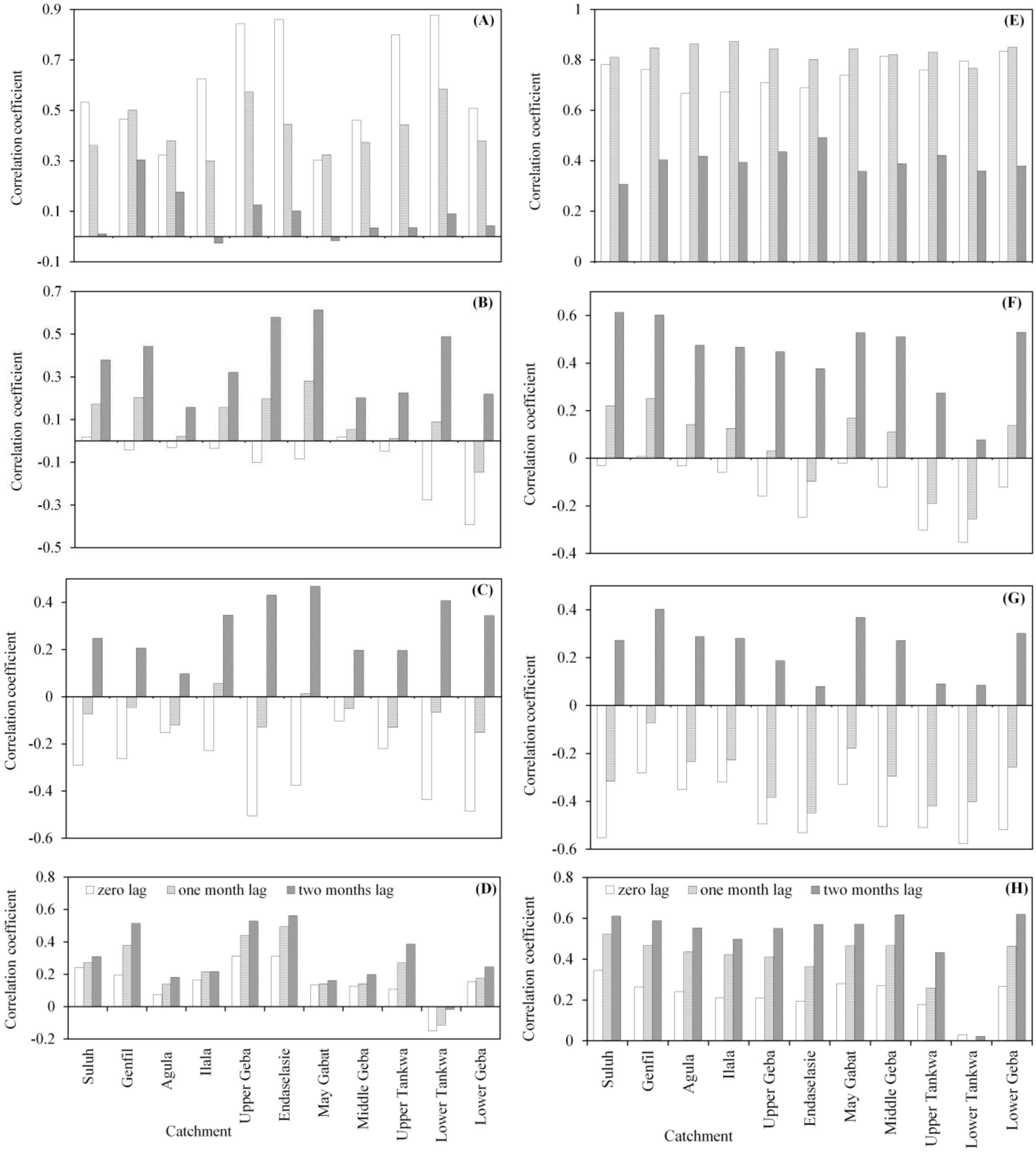

Fig. 8. Lagged correlations of monthly anomalies of streamflow and NPP versus lagged anomalies of precipitation, mean temperature, maximum temperature and minimum temperature. Graphs in the left row represent the lagged correlations of monthly streamflow versus lagged anomalies of precipitation (A), mean temperature (B), maximum temperature (C), and minimum temperature (D); Graphs in the right row represent the lagged correlations of monthly NPP versus lagged anomalies of precipitation (E), mean temperature (F), maximum temperature (G), and minimum temperature (H).

Notice that the correlation between streamflow and precipitation at one month lag becomes larger in the Genfel sub-catchment. However, the effects of precipitation persisted for up to one month in the other sub-catchments of the upper region of the catchment, suggests an underlying mechanises of water redistribution in the region. While the significant negative correlations of maximum temperature and positive correlations of minimum temperature at zero lag reflect the fact that warm, dry weather tends to deplete moisture through evaporation and transpiration.

It was found that NPP for all the sub-catchments showed significant positive correlation at zero lag with precipitation, and the effect will persist for two months in most area of the Geba catchment. Whereas 30%, and 90% of the sub-catchments NPP showed a significant positive one and two months lagged correlation, respectively, with mean temperature. 30%, and 20% showed a significant negative zero and one month lagged correlation with mean temperature, respectively. Significant negative correlation at zero lag with one month duration was also observed between NPP and monthly variation of maximum temperature in most of the sub-catchments. NPP showed a significant positive zero lagged correlation with minimum temperature, and the duration length of minimum temperature on NPP was extend for two months in most of the study area.

The significant positive correlation at zero lag with no duration between NPP for most of the sub-catchments and precipitation indicates the response of NPP to precipitation is instantaneous, as the study area found in semi-arid zone with mean annual precipitation ranges from of 552 to 767 mm, about 83% of the mean annual precipitation contributed in main rainy season and most of the plants were lacking water outside the rainy season, thus the response of vegetation to precipitation was immediate and could not persist for a long time (Ludwig et al., 2005; Wang et al., 2015). Precipitation infiltrated in the soil, is absorbed by the root system of vegetation and subsequently stored by the vegetation canopy and stems, resulting in delayed vegetation growth response to precipitation, which may explain the significant positive correlation at one month lag with two months duration.

Most of the sub-catchments, however have displayed significant negative zero-lag correlations between maximum temperature and NPP, which may be attributed to an increase in water stress in these water-deficient environments due to warmer temperature (Mohammed et al., 2004). The positive zero and one month lag correlations between minimum temperature and NPP in most of the sub-catchments reflect that their evidences of positive correspondence between NPP and temperature through enhancing an earlier initiation of the growing season and more robust plant production (Zhang et al 2013; Zhao and Running, 2010), however warmer temperature also have the effect of increasing evaporation and transpiration by vegetation leading to moisture stress (Hu et al., 2010; Braswell et al., 1997).

3.2.3. Impact of human activities

The results so far suggest that other than climate factors changed in the course of the investigated period, and in particular land use and land cover changes qualify for further consideration. Therefore, streamflow and NPP are shown and linearly regressed in Fig. 9 as a function of precipitation. The method assumes that, for a given catchment, the relationship between streamflow and NPP, and precipitation will remain unchanged unless catchment properties have been modified (Zhao et al., 2015). Based on the breaks identified in the Pettitt test analysis Fig. 4 and 6, and Appendix A (Table A.5), two periods were distinguished for the representative sub-catchments. In both of the sub-catchments, the correlation, judged from R^2-values, between streamflow and precipitation in the first period is larger than in the second period. Accordingly, in the second period, the changes in streamflow and NPP are influenced to a lesser degree by precipitation than in the first period. Moreover, the regression lines for streamflow in the first period were located either above (Suluh) or below (Genfel) the line for the second period, i.e., streamflow was stabilized at lower or higher levels.

For streamflow, the most likely reason for this difference could be the impact of human management, by measures such as diversions, earthen dams, and irrigated lands in and adjacent to the Suluh and Genfel sub-catchments. For instance the buffering effect of small water reservoirs behind dams is expected to decrease the direct correlation between rainfall and streamflow, and may stabilize flow rates at larger or smaller values, depending on e.g., water conservation measures that are taken upstream.

For NPP, correlations in both periods were small, but also decreased from period 1 to 2. Larger effects can be seen in the magnitude of NPP, which about doubled after period 1. Such a sudden and beneficial effect is very likely related to human interventions as ecological restoration and soil and water conservation measures.

The Pettitt test emphasizes the shifts in streamflow, and increase in NPP in most of the sub-catchments in 1990s and 2000s. Apparently, environmental rehabilitation programmes,

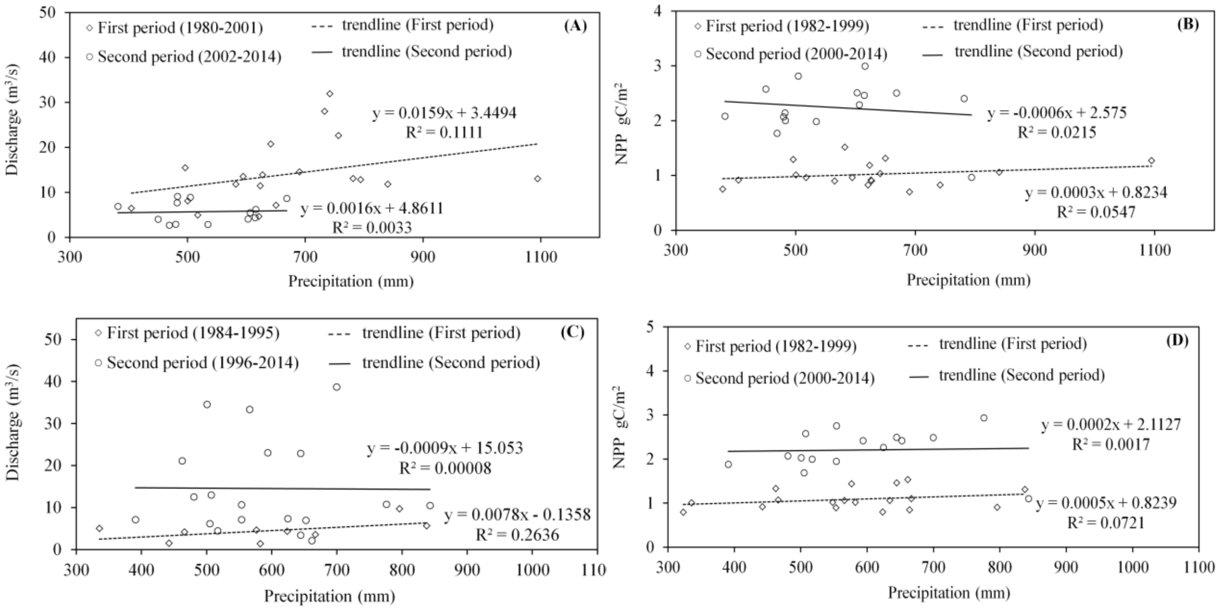

Fig. 9. Correlations between streamflow, NPP and precipitation in the Suluh (A) and (B) and Genfel (C) and (D) sub-catchments in the two different periods (first and second periods).

including soil and water conservation measures, construction of micro-dams, and ecological restoration measures implemented since the 1980s have had their benefits (Gebersamuel et al., 2010; Nyssen et al., 2010; Hargeweyn et al., 2006).

Environmental rehabilitation programmes were initiated in the 1980s. From then on, the area affected by ecological restoration and soil and water conservation measures expanded year by year, and the capacity of water storage in the catchment was gradually enhanced. After the implementation of these programmes and measures of soil and water conservation, land management improved greatly, drainage density and the rates of gully erosion decreased (Frankl et al., 2011; Descheemaeker et al., 2006), vegetation coverage improved (Nyssen et al., 2015; Teka D et al., 2013), and the hydrology changed (Taye et al., 2013; Nyssen et al., 2010; Haregeweyn et al., 2006) in most parts of northern Ethiopia.

Based on the Landsat images, land use and land cover (LULC) change were detected for the four years, 1984, 1995, 2003, and 2014 (Table 1), and the spatial LULC changes and accuracy assessments are presented in the supplementary information Section (Appendixes E). The dominant land use and land cover types in the catchment are crop land (including rain-fed areas and irrigated farm lands) and shrub covered areas. A reduction in tree covered areas from 3.8 to 2.8%, grass land from 13.2 to 8.7% and bare soil 11.5 to 7.95% cover in the catchment took place between 1984 and 2014 (see Table 1). During the 31-years period, the proportion of shrub covered areas increased by 19.12%, crop land by 5.1%, artificial surfaces by 58.06% and, water bodies increased by more than threefold. Although water bodies still covered a small proportion of the catchment in 2014, its change from the period 1984–2014 is large. The increase in shrub covered areas, artificial surfaces and water bodies was large during the time period 1995–2003, and 2003–2014 compared to the earlier time period 1984–1995, whereas both time periods saw similar declines in bare soil and grass land. Crop land increased moderately, whereas tree covered areas showed little change during the 31-years

Table 1. Summary of land use and land cover (1984–2014) coverage.

Land use	Area cover (ha.)				Cover change between periods (%)				
	1984	1995	2003	2014	1984-1995	1995-2003	2003-2014	1984-2014	1995-2014
Tree covered areas	19539.6	16454.4	13369.2	14397.6	-15.79	-18.75	7.69	-26.32	-12.50
Shrub covered areas	129064.2	131635.2	141405	153745.8	1.99	7.42	8.73	19.12	16.80
Grass land	67874.4	73530.6	62218.2	44735.4	8.33	-15.38	-28.10	-34.09	-39.16
Artificial surfaces	15940.2	17482.8	18511.2	25195.8	9.68	5.88	36.11	58.06	44.12
Crop land	222648.6	220077.6	229847.4	234475.2	-1.15	4.44	2.01	5.31	6.54
Bare soil	58953.03	54788.01	48314.232	40878.9	-7.06	-11.82	-15.39	-30.66	-25.39
Water bodies	179.97	231.39	534.768	771.3	28.57	131.11	44.23	328.57	233.33
Total	5142	5142	5142	5142					

Cover change between periods was calculated as $100\times(A_{final\ year} - A_{initial\ year})/A_{initial\ year}$, where A = area of the land use and land cover type.

period (see Table 1). Although it recovered between 2003 and 2014, tree covered areas was reduced in the earlier period, 1984–2003. Grass land increased between 1984 and 1993, but then declined between 2003 and 2014. The changes in LULC in the study area thus indicated that the pattern has changed significantly since 1990s (see Table 1, and Appendixes E), and could be contributed to the changes in streamflow and NPP in the region. The increase of shrub covered area and water bodies could be mainly ascribed to the implementations of land rehabilitation programme, through ecological restoration and soil and water conservation measures, in the region since 1980s.

The ecological restoration and soil and water conservation measures undertaken in the Geba catchment included both physical measures (e.g., creation of terraces and stone bunds, and micro-dam construction) and biological measures (e.g., afforestation and grass planting). Establishment of terraces and stone bunds can reduce the slope gradient and change the local micro topography. The establishment of terraces and stone bunds effectively improve the infiltration rate of water flow, thus delaying and reducing runoff generation. Similarly, micro-dam construction can harvest the runoff and re-distribute the seasonal water resource within a year, and also adjust the inter-annual streamflow distribution. Moreover the use of water during the growing period, trees, shrubs, and grass intercept precipitation, enhance evaporation, improve soil structure, increase infiltration, and thus reduce the amount of runoff. Thus, the implementation of these land rehabilitation measures not only decreased the possibility of runoff generation from precipitation, but also retained more runoff on the hillsides instead of flowing into river channel. According to BoARD (2015), the region claims that about 80% of agricultural field as already being under soil and water conservation management, and about 1.96 million hectares (35% of Tigray region) of land is rehabilitated by ecological restoration measures. In the region, 54 micro-dams from 1992–2002 (Haregeweyn et al., 2008; Yazew et al., 2005), and 87 micro-dams from 1992–2009 (BoWRD, 2009) were constructed.

The drivers and related changes discussed above may therefore influence ecosystem functioning in the catchment through their impact on vegetation coverage and water amount and distribution. This may also lead to a decrease in streamflow and increased in the NPP at the catchment.

Conclusions

Northern Ethiopian highlands in general and the study area are characterized by rugged topography, both intense rainfall and frequent droughts, and sparse vegetation cover. Therefore, climate variability have a strong negative impact on agricultural production and hydrology. Numerous mitigation and land rehabilitation measures, such as the construction of micro-dams, stone bunds, check dams, exclosures, and reforestation, have been introduced since 1980s, but not always successfully. For an accurate assessment of controlling factors, this study investigates trends and change points in precipitation, temperature, streamflow, and net primary productivity (NPP), as well as relationships between these variables and their annual and seasonal variation for the study catchment.

The findings showed both significant increasing and decreasing trends for temperature, and no statistically significant trends for precipitation with most stations, both over the years and over each season, except for a few stations. For all investigated periods of annual and all seasons except the dry season, more stations showed a decreasing trend of monthly mean streamflow. The stations with significant negative trends of annual and seasonal streamflow are mainly distributed in the upper region of the catchment. From 1982 to 2014, the average annual NPP in the Geba catchment demonstrated a generally increasing trend. The increase rate was 0.068 gC/m^2 per year. NPP increased significantly in all of the sub-catchments, and the average annual NPP increase was the largest in the upper region of the catchment. Though change points differ somewhat in time for the different variables. However, it is clear that most changes occurred in the period between 1995 and 2004, as both the breakpoint analysis and the changes in land use and land cover illustrate.

The correlation coefficients of the relationships between the mean values and CVs for streamflow, NPP, and climatic variables indicated streamflow, however, was most strongly correlated with precipitation, and NPP was controlled mostly by precipitation and maximum temperature highlighting the role of climate variability in the changes of streamflow and NPP. The time-immediate/lagged cross-correlations between streamflow and NPP, and climatic variables are responses from simultaneous biophysical alterations and delayed biogeochemical adjustments, respectively. It has been found that the correlation between streamflow and precipitation at one month lag becomes larger in the upper region than the lower and middle regions, which implies that streamflow is more sensitive to precipitation in the lower and middle regions than the upper region. However, human activities play a more important role in streamflow change.

Human activities, and related land use and land cover changes are shown to be the important influencing factors that affect streamflow and NPP in the catchment. Based on the breaks identified in the Pettitt test analysis, streamflow and NPP data were divided into first period and second period for the representative sub-catchments, Suluh and Genfel, in the upper region. In the first period, climate change played a dominant role. In the second period, climate change continued to influence the streamflow, however the effect from human activities was enhanced significantly.

Therefore, climate and human activities jointly affect the spatiotemporal variation patterns of the streamflow and NPP in the Geba catchment. Precipitation and maximum temperature were the dominant climatic variables, also human activities, such as soil and water conservation measures, construction of micro-dams, and ecological restoration measures has a profound and beneficial effects on streamflow and NPP variation. Accordingly, the selection of water and land management options may also have to be apprehensive of differences between catchments or sub-catchments.

Acknowledgements

We gratefully acknowledge the financially support by the Netherlands Government Fellowship Programme (NUFFIC-NFP). CIRCLE (Climate Impact Research Capacity and Leadership Enhancement) project (Co-operated by African Academic Science (AAS), and UKAID), Mekelle University and Wageningen University are acknowledged for their support. We would also like to thank the Ethiopian Minster of Water, Irrigation, and Energy and the Ethiopian National Metrological Service and the MU-IUC project for providing hydrological and meteorological data.

Appendix A, B, C, D and E. Supplementary information

Appendices are presented in the supplementary information Section.

References

Alemayehu F, Taha N, Nyssen J, Girma A, Zenebe A, Behailu M, Deckers J, Poesen J (2009) The impacts of watershed management on land use and land cover dynamics in Eastern Tigray (Ethiopia). Resour Conserv Recy 53: 192–198.

Araya A, Stroosnijder L (2011) Assessing drought risk and irrigation need in northern Ethiopia. Agric For Meteorol 151: 425–436.

Asfaw B (2014) Modeling the Effect of Climate and Land Use Change on the Water Resources in Northern Ethiopia: the Case of Suluh River Basin. PhD thesis, Freie Universität Berlin, Germany.

Berhane G, Martens K, Farrah N, Walraevens K (2012) Water leakage investigation of micro-dam reservoirs in Mesozoic sedimentary sequences in Northern Ethiopia. Journal of African Earth Sciences 79: 98–110. http://dx.doi.org/10.1016/j.jafrearsci.2012.10.004.

Bewket W, Conway D (2007) A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia. International Journal of Climatology 27: 146–1477. DOI: http://dx.doi.org/10.1002/joc.1481.

Beyene AN (2015) Precipitation and Temperature Trend Analysis in Mekelle City, Northern Ethiopia, the Case of Illala Meteorological Station. Journal of Environment and Earth Science 5 (19). ISSN: 2224-3216. http://www.iiste.org/Journals/index.php/JEES/ article/viewFile/26529/27169.

BoARD (2015) Soil and Water Conservation Report, Tigray Bureau of Agriculture and Rural Development, Mekelle, Ethiopia.

BoWRD (2009) Design and construction of micro earth dams in Tigray. Annual report 2009, Bureau of Water Resources Development, Mekelle, Ethiopia.

Braswell BH, Schimel DS, Linder E, Moore B, 1997. The response of global terrestrial ecosystems to inter-annual temperature variability. Science 278: 870–2.

Camberlin (1997) Rainfall anomalies in the source region of the Nile and their connection with the Indian Summer Monsoon. J. Climate 10: 1380–92.

Canadell JG, Pataki DE, Pitelka LF (2006) Terrestrial ecosystems in a changing world. Springer –Verlag, Berlin. ISBN: 978-3-540-32730-1.

Checchi F, and Robinson WC (2013) Mortality among populations of southern and central Somalia affected by severe food insecurity and famine during 2010–2012. FAO and FEWS NET: 87.

Conway D (2000) The climate and hydrology of the Upper Blue Nile. Geogr. J. 166(1): 49–62.

Conway D, Mould C, Bewket W (2004) Over one century of rainfall and temperature observations in Addis Ababa, Ethiopia. International Journal of Climatology 24: 77–91. DOI: http://dx.doi.org/10.1002/joc.989.

Conway D, Schipper ELF (2011) Adaptation to climate change in Africa: challenges and opportunities identified from Ethiopia. Glob Environ Chang 21:227–237. DOI: http://dx.doi.org/10.1016/j.gloenvcha.2010.07.013.

Descheemaeker K, Nyssen J, Poesen J, Haile M, Muys B, Raes D, Moeyersons J, Deckers J (2006) Soil and water conservation through forest restoration in exclosures of the Tigray highlands. Journal of the Drylands 1(2): 118–133.

Dettinger Md, Diaz Hf (2000) Global Characteristics of Stream Flow Seasonality and Variability. Journal of Hydrometeorology 1. DOI: http://dx.doi.org/10.1175/1525-7541(2000)001<0289: GCOSFS >2.0.CO;2.

Diro GT, Grimes DIF, Black E (2010). Teleconnections between Ethiopian summer rainfall and sea surface temperature: Part I—Observation and modeling. Clim. Dyn. DOI: http://dx.doi.org/10.1007/s00382-010-0837-8.

Edossa DC, Babel MS, Gupta AD (2010) Drought Analysis in the Awash River Basin, Ethiopia. Water Resour Manage 24:1441–1460. DOI: http://dx.doi.org/10.1007/s11269-009-9508-0.

Eklundh L, Pilesjö P (1990) Regionalization and spatial estimation of Ethiopian mean annual rainfall. International Journal of Climatology 10 (5): 473–494. DOI: http://dx.doi.org/10.1002/joc.3370100505.

FAO, United Nations Food and Agriculture Organization (2014) Global Land Cover SHARE (GLC-SHARE) database. Beta-Release Version 1.0–2014. Rome, Italy. http://www.glcn.org/databases/lc_glcshare_downloads_en.jsp.

FAO (1998) Soil and Terrain Database for Northeastern Africa: Crop Production System Zones of the IGAD Sub-region. FAO Land and Water Digital Media Series 2.

FEWS (Famine Early Warning System) NET (2016) Food Security Outlook, Ethiopia: Largescale food security emergency projected for 2016: 19.

FEWS (Famine Early Warning System) (2003) FEWS Ethiopia Food Security Update, 14 August 2003. http//www.fews.net.

Feoli E, Vuerich LG, Zerihun W (2002) Evaluation of environmental degradation in Northern Ethiopia using GIS to integrate vegetation, geomorphological, erosion and socio-economic factors. Agriculture Ecosystems and Environment 91 (1-3): 313–325.

Fik TJ, Mulligan GF (1998) Functional form and spatial interaction models. Environ. Plan. A. 30(8):1497-1507. DOI: http://dx.doi.org/10.1068/a301497.

Frankl A, Nyssen J, de Dapper M, Haile M, Billi P, Munro RN, Deckers J, Poesen J (2011) Linking long-term gully and river channel dynamics to environmental change using repeat photography (North Ethiopia). Geomorphology 129: 238–251. DOI: http://dx.doi.org/10.1016/j.geomorph.2011.02.018.

Gebrehiwot T, van der Veen A (2013) Assessing the evidence of climate variability in the northern part of Ethiopia. Journal of Development and Agricultural Economics 5 (3): 104–119. DOI: http://dx.doi.org/ 10.5897/JDAE12.056.

Gebresamuel G, Singh BR, Dick Ø (2010) Land-use changes and their impacts on soil degradation and surface runoff of two catchments of Northern Ethiopia. Acta Agriculturae

Scandinavica, Section B-Soil & Plant Science 60 (3): 211-226. DOI: http://dx.doi.org /10.1080/09064710902821741.

Gebresamuel G, Singh BR, Nyssen J, Borrosen T (2009) Runoff and sediment-associated nutrient losses under different land uses in Tigray, Northern Ethiopia. Journal of Hydrology 376: 70–80. DOI: http://dx.doi.org/10.1016/j.jhydrol.2009.07.066

Gebreselassie MG, Moges SA (2015) Spatial and Temporal Variability of Rainfall at Seasonal and Annual Time Scales at Tekeze River Basin, Ethiopia. Journal of Natural Sciences Research 5 (19). ISSN: 2224-3186. DOI: http://www.iiste.org/Journals/index. php/JNSR/article/viewFile/26484/27140.

Gebreyohannes T, De Smedt F, Walraevens K, Gebresilassie S, Hussien A, Hagos M, Amare K, Deckers J, Gebrehiwot K, 2013. Application of a spatially distributed water balance model for assessing surface water and groundwater resources in the Geba basin, Tigray, Ethiopia. Journal of Hydrology 499: 110-123. DOI: http://dx.doi.org/10.1016/j .jhydrol. 2013.06.026.

Gete Z, Hurni H (2001) Implications of land use and land cover dynamics for mountain resource degradation in the northwestern Ethiopian highlands. Mountain Research and Development 21: 184–191.

Gissila T, Blak E, Grimes DIF, Slingo JM (2004) Seasonal forecasting of the Ethiopian summer rains. Int. J. Clim. 24: 1345–1358.

Goitom H (2012) Modeling of Hydrological Processes in the Geba River Basin, Northern Ethiopia. PhD thesis, Vrije Universiteit Brussel, Belgium.

Gong W, Wang L, Lin A, Zhang M (2012) Evaluating the monthly and interannual variation of net primary production in response to climate in Wuhan during 2001 to 2010. Geosciences Journal 16 (3): 347 – 355. DOI: http://dx.doi.org/10.1007/s12303-012-0025-4.

Hadgu G, Tesfaye K, Mamo G (2015) Analysis of climate change in Northern Ethiopia: implications for agricultural production. Theoretical Application Climatology 121 (3): 733–747. DOI: http://dx.doi.org/10.1007/s00704-014-1261-5.

Hao W, Guohua L, Zongshan L, Xin Y, Meng W, Li G (2016) Impacts of Climate Change on Net Primary Productivity in Arid and Semiarid Regions of China. Chinese Geographical Science 26 (1): 35–47. DOI: http://dx.doi.org/10.1007/s11769-015-0762-1.

Haregeweyn N, Tesfaye S, Tsunekawa A, Tsubo M, Meshesha DT, Adgo E, Elias A (2015) Dynamics of Land Use and Land Cover and Its Effects on Hydrologic Responses: case study of the Gilgel Tekeze Catchment in the Highlands of Northern Ethiopia. Environ Monit Assess 87: 4090. DOI: http://dx.doi.org/10.1007/s10661-014-4090-1.

Haregeweyn N, Poesen J, Nyssen J, Govers G, Verstraeten G, de Vente J, Deckers J, Moeyersons J, Haile M (2008) Sediment yield variability in Northern Ethiopia: A quantitative analysis of its controlling factors. Catena 75: 65–76. DOI: http://dx.doi.org/ 10.1016/j.catena.2008.04.011.

Haregeweyn N, Poesen J, Nyssen J, De Wit J, Mitiku Haile, Govers G, Deckers J (2006) Reservoir sedimentation in Tigray (Northern Ethiopia): Characteristics and sediment deposition problems. Land Degradation Development 17: 211–230. DOI: http://dx. doi.org/10.1002/ldr.698.

Haregeweyn N, Poesen J,, Nyssen J, Verstraeten G, de Vente J, Govers G, Deckers S, Moeyersons J (2005). Specific sediment yield in Tigray-Northern Ethiopia: Assessment and semi-quantitative modelling. Geomorphology 69: 315–331. DOI: http://dx.doi.org/ 10.1016/j.geomorph.2005.02.001.

Hu MQ, Mao F, Sun H, Hou YY (2010) Study of normalized difference vegetation index variation and its correlation with climate factors in three river source region. Int J App Earth Obeserv Geoinf. DOI: http://dx.doi.10.1016/j/jag.2010.06.003.

Huntingford C, Cox PM, Lenton TM (2000) Contrasting response of a simple terrestrial ecosystem model to global change. Ecol Model 134: 41-58.

Hurni H, Tato K, Zeleke G (2005) The implication of changes in population, Land use and land management for surface runoff in the upper Nile basin area of Ethiopia. Mountain Research and Development 25(2): 147–154. DOI: http://dx.doi.org/10.1659/0276-4741 (2005)025[0147:TIOCIP]2.0.CO;2.

IPCC-Intergovernmental Panel on Climate Change (2013) Climate Change 2013: the physical science basis. In: Stocker et al. (Eds.), Fifth Assessment Report of the Intergovernmental Panel on Climate Change (contribution of Working Group I). Cambridge University Press, Cambridge, U. K.

Jacob M, Frankl A, Beeckman H, Mesfin G, Hendrickx M, Etefa Guyassa, Nyssen J (2015) North Ethiopian Afro-alpine tree line dynamics and forest cover change since the early 20th century. Land Degrad Dev 501(26): 654–664. DOI: http://dx.doi: 10.1002/ldr.2320.

Jones JA, Creed IF, Hatch KL, Warren RJ, Adams MB, Benson MH, Boose E, Brown WA, Campbell JL, Covich A, Clow DW, Dahm CN, Elder K, Ford CR, Grimm NB, Henshaw DL, Larson KL, Miles ES, Miles KM, Sebestyen SD, Spargo AT, Stone AB, Vose JM, Williams MW (2012) Ecosystem Processes and Human Influences Regulate Streamflow Response to Climate Change at Long-Term Ecological Research Sites. BioScience 62 (4): 390-404. DOI: https://doi.org/10.1525/bio.2012.62.4.10.

Kendall MG (1975) Rank correlation methods. Charles Griffin, London.

Knapp AK, Smith MD (2001) Variation among biomes in temporal dynamics of aboveground primary production. Science 291 (5503): 481-484. DOI: http://dx.doi.org/10.1126/ science. 291.5503.481.

Krauer J (1988) Rainfall, erosivity and isoerodent map of Ethiopia. Soil Conservation Research Project. Research Report 15: 132. University of Berne, Switzerland.

Lanckriet S, Rucina S, Frankl A, Ritler A, Gelorini V, Nyssen J (2015) Nonlinear vegetation cover changes in the North Ethiopian Highlands: Evidence from the Lake Ashenge closed basin. Science of the Total Environment 536: 996–1006. DOI: http://dx.doi.org/10.1016/ j.scitotenv.2015.05.122 .

Liu BM, Collick AS, Zeleke G, Adgo E, Easton ZM, Steenhuis TS (2008) Rainfall-discharge relationships for a monsoonal climate in the Ethiopian highlands. Hydrological Processes 22(7): 1059-1067.

Ludwig JA, Wilcox BP, Breshears DD, Tongway DJ, and Imeson AC (2005) Vegetation patches and runoff–erosion as interacting ecohydrological processes in semiarid landscapes. Ecology 86(2): 288–297.

Mann HB (1945) Nonparametric tests against trend, Econometrica: Journal of the Econometric Society 13(3): 245-259. DOI: http://dx.doi.org/10.2307/1907187.

Marshall M, Lamb H, Davies S, Leng M, Kubsa Z, Umer M, Bryant C (2009) Climatic change in northern Ethiopia during the past 17,000 years: a diatom and stable isotope record from Lake Ashenge. Palaeogeogr. Palaeoclimatol. Palaeoecol. 279: 114–127. DOI: http://dx.doi.org/10.1016/j.palaeo.2009.05.003.

McSweeney C, New Lizcano G (2008) UNDP Climate Change Country Profiles – Ethiopia. http://countryprofiles.geog.ox.ac.uk.

Melesse AM, Abtew W, Setegn SG (2014) Nile River Basin: Ecohydrological Challenges, Climate Change and Hydropolitics. Springer International Publishing, Switzerland. ISBN: 978-3-319-02720-3. DOI: http://dx.doi.org/10.1007/978-3-319-02720-3.

Meze-Hausken E (2004) Contrasting climate variability and meteorological drought with perceived drought and climate change in northern Ethiopia. Clim. Res. 27: 19–31.

Mohamed MA, Babiker IS, Chen ZM, Ikeda K, Ohta K, Kato K (2004) The role of climate variability in the inter-annual variation of terrestrial net primary production (NPP). Science of the Total Environment 332: 123−137.

NMA (National Meteorological Agency, Ethiopia) (2007) Initial National Communication of Ethiopia to the United Nations Framework Convention on Climate Change (UNFCCC). Addis Ababa, Ethiopia.

Nyssen J, Frankl A, Zenebe A, Deckers J, Poesen J (2015) Land Management in the Northern Ethiopian Highlands: Local and global perspectives; past, present and future. Land Degradation Development 26: 759–764. DOI: http://dx.doi.org/10.1002/ldr.2336.

Nyssen J, Clymans W, Descheemaeker K, Poesen J, Vandecasteele I, Vanmaercke M, Haile M, Haregeweyn N, Moeyersons J, Martens K, Zenebe A, van Camp M, Gebreyohannes T, Deckers J, Walraevens K (2010) Impact of soil and water conservation on catchment hydrological response: a case in northern Ethiopia. Hydrological Processes 24: 1880–1895. DOI: http://dx.doi.org/10.1002/hyp.7628.

Nyssen J, Vandenreyken H, Poesen J, Moeyersons J, Deckers J, Haile M, Salles C, Govers G (2005) Rainfall erosivity and variability in the Northern Ethiopian Highlands. Journal of Hydrology 311(1-4): 172-187. DOI: http://dx.doi.org/10.1016/j.jhydrol.2004.12.016.

Nyssen J, Poesen J, Moeyersons J, Deckers J, Mitiku H, Lang A (2004) Human impact on the environment in the Ethiopian and Eritrean highlands – A state of the art. Earth-Science Reviews 64: 273–320.

Osman M, Sauerborn P (2002) A preliminary assessment of characteristics and long term variability of rainfall in Ethiopia-Basis for sustainable land use and resource management. Paper presented on the International Agricultural Research for Development Conference, October 9–11, Witzenhausen.

Pankhurst R (1985) The History of Famine and Epidemics in Ethiopia. RRC: Addis Ababa.

Peng DL, Huang JF, Cai CX, Deng R, Xu JF (2008) Assessing the response of seasonal variation of net primary productivity to climate using remote sensing data and geographic information system techniques in Xinjiang. Journal of Integrative Plant Biology 50: 1580−1588.

Peng H, Tague C, Jia Y (2015) Evaluating the eco-hydrologic impacts of reforestation in the Loess Plateau, China, using an eco-hydrologic model. Ecohydrology 9 (3): 498-513. DOI: http://dx.doi.org/10.1002/eco.1652.

Pettitt A (1979) A non-parametric approach to the change-point problem. Applied statistics 28 (2): 126-135. DOI: http://dx.doi.org/10.2307/2346729.

Piao SL, Fang JY, Guo QH (2001) Application of the CASA model to the estimation of Chinese terrestrial net primary productivity. Acta Phytoecologica Sinica 25: 603–608. http://en.cnki.com.cn/Article_en/CJFDTOTAL-ZWSB200105014.htm.

Potter C, Klooster S, Genovese V (2012) Net primary production of terrestrial ecosystems from 2000 to 2009. Climatic Change. DOI: http://dx.doi.org/10.1007/s10584-012-0460-2.

Potter C, Klooster S, Huete A, Genovese V, Bustamante M, Ferreira LG, Cosme de Oliveira R Jr, Zepp R (2009) Terrestrial carbon sinks in the Brazilian Amazon and Cerrado region predicted from MODIS satellite data and ecosystem modeling. Biogeosciences 6 (6): 937-945. DOI: http://dx.doi.org/10.5194/bg-6-937-2009.

Potter C, Klooster S, Myneni R, Genovese V, Tan P, Kumar V (2003) Continental scale comparisons of terrestrial carbon sinks estimated from satellite data and ecosystem modeling 1982–98. Glob Planet Chang 39: 201–213. DOI: http://dx.doi.org/10.1016/j.gloplacha.2003.07.001.

Potter CS, Randerson JT, Field CB, Matson PA, Vitousek PM, Mooney HA, Klooster SA (1993) Terrestrial ecosystem production: a process model based on global satellite and surface data. Global Biogeochemical Cycles 7(4): 811–841. DOI: https://doi.org/ 10.1029/93GB02725.

Segele ZT, Lamb PJ (2005) Characterization and variability of Kiremt rainy season over Ethiopia. Meteorol. Atmos. Phys. 89: 153–180.

Seleshi Y, Camberlin P (2006) Recent changes in dryspell and extreme rainfall events in Ethiopia. Theor. Appl. Climatol. 83: 181–191.

Seleshi Y, Zanke U (2004) Recent changes in rainfall and rainy days in Ethiopia. International Journal of Climatology 24(8): 973-983. DOI: http://dx.doi.org/10.1002/joc.1052.

Seleshi Y, Demaree GR (1995) Rainfall variability in the Ethiopian and Eritrean highlands and its links with the Southern Oscillation Index. J. Biogeogr. 22: 945–952.

Sen PK (1968) Estimates of the regression coefficient based on Kendall’s tau. J Am Stat Assoc 63: 1379–1389.

Shanko D, Camberlin P (1998) The effects of the Southwest Indian Ocean tropical. International Journal of Climatology 1388: 1373 – 1388. DOI: http://dx.doi.org/10.1002/(SICI)1097-0088(1998100)18:12<1373::AID-JOC313>3.0.CO;2-K.

Sykes MT, Prentice IC, Laarif F (1999) Quantifying the impact of global climate change on potential natural vegetation. Climatic Change 41(1): 37–52. DOI: http://dx.doi.org/10.1023/A:1005435831549.

Tabari H, Taye MT, Willems P (2015) Statistical assessment of precipitation trends in the upper Blue Nile River basin. Stoch Environ Res Risk Assess 29: 1751–1761. DOI http://dx.doi.org/10.1007/s00477-015-1046-0.

Taye G, Poesen J, Van Wesemael B, Vanmaerck M, Teka D, Deckers J, Goosse T, Maetens W, Nyssen J, Hallet V, Haregeweyn N (2013) Effects of land use, slope gradient, and soil and water conservation structures on runoff and soil loss in semi-arid Northern Ethiopia. Physical Geography 34 (3): 236–259. http://dx.doi.org/10.1080/02723646.2013.832098.

Taye MT, Willems P (2012) Temporal variability of hydroclimatic extremes in the Blue Nile basin. Water Resources Research 48 (3):1–14. DOI: DOI: http://dx.doi.org/10.1029/2011 WR011466.

Taye MT, Willems P (2013) Identifying sources of temporal variability in hydrological extremes of the upper Blue Nile basin. Journal of Hydrology 499: 61–70. DOI: http:// dx.doi.org/10.1016/j.jhydrol.2013.06.053.

TECSULT: Ethiopian Energy II Project (2004) Woody Biomass Inventory and Strategic Planning Project (WBISPP) - Phase 2 - Terminal Report, Ministry of Agriculture, Addis Ababa, Ethiopia.

Teferi ED, Uhlenbrook S, Bewket W (2015) Inter-annual and seasonal trends of vegetation condition in the Upper Blue Nile (Abbay) basin: dual scale time series analysis. Earth Syst. Dynam. 6: 617–636. DOI: http://dx.doi.org/10.5194/esd-6-617-2015.

Teferi ED (2015) Soil hydrological impacts and climatic controls of land use and land cover changes in the Upper Blue Nile (Abay) basin, Ethiopia. Dissertation UNESCO-IHE/ TU Delft, the Netherlands.

Teka D, van Wesemael B, Vanacker V, Poesen J, Hallet V, Taye G, Deckers J, Haregeweyn N (2013) Evaluating the performance of reservoirs in semi-arid catchments of Tigray:

Tradeoff between water harvesting and soil and water conservation. Catena 110: 146–154. DOI: http://dx.doi.org/10.1016/j.catena.2013.06.001.

Teka K, Van Rompaey A, Poesen J (2013) Assessing the role of policies on land use change and agricultural development since 1960s in northern Ethiopia. Land Use Policy 30: 944–951. DOI: http://dx.doi.org/10.1016/j.landusepol.2012.07.005.

Tekleab S, Mohamed Y, Uhlenbrook S (2013) Hydro-climatic trends in the Abay/Upper Blue Nile basin, Ethiopia. Physics and Chemistry of the Earth 61–62: 32–42. DOI: http://dx.doi.org/10.1016/j.pce.2013.04.017.

Tessema Z, Lamb P (2003) Inter annual variability of growing season over drought prone areas of Ethiopia. CLIVAR Exchange 8 (2/3): 36–39.

Tielens S (2012) Towards a soil map of the Geba catchment using benchmark soils. MSc thesis, Katholieke Universiteit Leuven, Belgium.

Tucker CJ, Pinzon JE, Brown ME, Slayback DA, Pak EW, Mahoney R, Vermote EF, El Saleous N (2005) An extended AVHRR 8 km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. International Journal of Remote Sensing 26 (20): 4485–4498. DOI: http://dx.doi.org/10.1080/01431160500168686.

Twine TE, Kucharik CJ (2009) Climate impacts on net primary productivity trends in natural and managed ecosystems of the central and eastern United States. Agricultural and Forest Meteorology 149 (12): 2143–2161. DOI: http://dx.doi.org/10.1016/j.agrformet.2009.05.012.

Vanmaercke M, Zenebe A, Poesen J, Nyssen J, Verstraeten G, Deckers J (2010) Sediment dynamics and the role of flash floods in sediment export from medium-sized catchments: a case study from the semi-arid tropical highlands in northern Ethiopia. Journal of Soils and Sediments 10: 61–627. DOI: http://dx.doi.org/10.1007/s11368-010-0203-9.

Viste E, Korecha D, Sorteberg A (2012) Recent drought and precipitation tendencies in Ethiopia. Theor. Appl. Climatol. DOI: http://dx.doi.org/10.1007/s00704-012-0746-3.

Wang L, Manzoni S, Ravi S, Riveros-Iregui D, Caylor K (2015) Dynamic interactions of ecohydrological and biogeochemical processes in water-limited systems. Ecosphere 6(8): 133. DOI: http://dx.doi.org/10.1890/ES15-00122.1.

Witte JPM, Runhaar J, Ek R van, Hoek van der DCJ, Bartholomeus RP, Batelaan O, van Bodegom PM, Wassen MJ, van der Zee SEATM (2012) An Ecohydrological Sketch of Climate Change Impacts on Water and Natural Ecosystems for the Netherlands: Bridging the Gap between Science and Society. Hydrol. Earth Syst. Sci. 16: 3945–3957. DOI: http://dx.doi.org/10.5194/hess-16-3945-2012.

Yang SL, Liu Z, Dai SB, Gao ZX, Zhang J, Wang HJ, Luo XX, Wu CS, Zhang Z (2010) Temporal variations in water resources in the Yangtze River (Changjiang) over the Industrial Period based on reconstruction of missing monthly discharges. Water Resources Research 46 (10). DOI: http://dx.doi.org/10.1029/2009WR008589.

Yazewu E (2005) Development and management of irrigated lands in Tigray, Ethiopia. PhD thesis, Wageningen University, the Netherlands.

Yu D, Shi P, Shao H, Zhu W, Pan Y (2009) Modelling net primary productivity of terrestrial ecosystems in East Asia based on an improved CASA ecosystem model. International Journal of Remote Sensing 30 (18): 4851–4866. DOI: http://dx.doi.org/10.1080/01431160802680552.

Yue S, Pilon P, Phinney B (2003) Canadian stream flow trend detection: impacts of serial and cross-correlation. Hydrological Science Journal 48 (1): 51–63. DOI: http://dx.doi.org/10.1623/hysj.48.1.51.43478.

Zenebe A (2009) Assessment of spatial and temporal variability of river discharge, sediment yield and sediment-fixed nutrient export in Geba River catchment, northern Ethiopia. Dissertation, Katholieke Universiteit, Leuven.

Zenebe A, Vanmaercke M, Poesen J, Verstraeten G, Haregeweyn N, Haile M, Amare K, Deckers J, Nyssen J (2013) Spatial and temporal variability of river flows in the degraded semi-arid tropical mountains of northern Ethiopia. Zeitschrift für Geomorphologie 57 (2): 143–169. DOI: http://dx.doi.org/10.1127/0372-8854/2012/0080.

Zhang X, Lu X, Wang X (2013) Spatial-Temporal NDVI Variation of Different Alpine Grassland Classes and Groups in Northern Tibet from 2000 to 2013. Mountain Research and Development 35(3): 254–263. DOI: http://dx.doi.org/10.1659/MRD-JOURNAL-D-14-0011 0.1.

Zhao M, Running S W (2010) Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science 329 (5994): 940–943. DOI: http://dx.doi .org/10.1126/science.1192666.

Zhao J, Huang Q, Chang J, Liu D, Huang S, Shi X (2015) Analysis of temporal and spatial trends of hydro-climatic variables in the Wei River Basin. Environmental Research, 139: 55–64. DOI: http://dx.doi.org/10.1016/j.envres.2014.12.028.