Hydrol. Earth Syst. Sci., 21, 2127–2142, 2017
www.hydrol-earth-syst-sci.net/21/2127/2017/
doi:10.5194/hess-21-2127-2017

Hydrology and
Earth System
Sciences
Open Access

Temporal and spatial changes of rainfall and streamflow in the Upper Tekezē–Atbara river basin, Ethiopia

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Received: 23 June 2016 – Discussion started: 29 August 2016
Revised: 28 February 2017 – Accepted: 27 March 2017 – Published: 19 April 2017

Abstract. The Upper Tekezē–Atbara river sub-basin, part of the Nile Basin, is characterized by high temporal and spatial variability of rainfall and streamflow. In spite of its importance for sustainable water use and food security, the changing patterns of streamflow and its association with climate change is not well understood. This study aims to improve the understanding of the linkages between rainfall and streamflow trends and identify possible drivers of streamflow variabilities in the basin. Trend analyses and change-point detections of rainfall and streamflow were analysed using Mann–Kendall and Pettitt tests, respectively, using data records for 21 rainfall and 9 streamflow stations. The nature of changes and linkages between rainfall and streamflow were carefully examined for monthly, seasonal and annual flows, as well as indicators of hydrologic alteration (IHA).

The trend and change-point analyses found that 19 of the tested 21 rainfall stations did not show statistically significant changes. In contrast, trend analyses on the streamflow showed both significant increasing and decreasing patterns. A decreasing trend in the dry season (October to February), short season (March to May), main rainy season (June to September) and annual totals is dominant in six out of the nine stations. Only one out of nine gauging stations experienced significant increasing flow in the dry and short rainy seasons, attributed to the construction of Tekezē hydropower dam upstream this station in 2009. Overall, streamflow trends and change-point timings were found to be inconsistent among the stations. Changes in streamflow without significant change in rainfall suggests factors other than rainfall drive the change. Most likely the observed changes in streamflow regimes could be due to changes in catchment characteristics of the basin. Further studies are needed to verify and quantify the hydrological changes shown in statistical tests by identifying the physical mechanisms behind those changes. The findings from this study are useful as a prerequisite for studying the effects of catchment management dynamics on the hydrological variabilities in the basin.

1 Introduction

Recent changes in climatic conditions combined with other anthropogenic factors have increased the concern of the international community for water resources management in basins (Jones et al., 2015; Zhang et al., 2008). Understanding climate change and its impact on hydrological variability is important for water management, and thus has received attention from researchers in different parts of the world (e.g. Kim et al., 2008; Ma et al., 2008; Pano et al., 2010; Tekleab et al., 2013; Wang et al., 2013; Zhan et al., 2014; Zhao et al., 2015). These studies investigate how climate change, reflected in changing rainfall patterns, affects the hydrological regimes of river basins.

Identifying the trends and linkages between rainfall and streamflow is fundamental to understanding the influence of climate change on the hydrological variability of a basin. Many studies (e.g. IPCC, 2013; Shi et al., 2013; Tekleab et al., 2013; Tesemma et al., 2010; Zhao et al., 2015) have

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shown that rainfall is the primary atmospheric factor that directly affects the streamflow patterns. The impact of climate change on hydrology varies from place to place. For example, Ma et al. (2008) for the arid region of north-west China, Zhang et al. (2011) for China, Zhao et al. (2015) for the Wei River basin of China, Love et al. (2010) for the Limpopo River of southern Africa and Abeysingha et al. (2015) for the Gomti River basin in northern India found that a decreasing trend of rainfall resulted in a significant reduction in streamflow. In contrast, Masih et al. (2011) in the Zagros mountains of Iran, Wilk and Hughes (2002) in southern India and Abdul Aziz and Burn (2006) in the Mackenzie River basin of Canada reported that a trend of increasing rainfall has significantly increased river flows. There are also a number of studies (e.g. Tekleab et al., 2013; Gebremicael et al., 2013; Wang et al., 2015; Hannaford, 2015; Saraiva-Okello et al., 2015) who found that changes in rainfall are not sufficient to explain the trends in the streamflow.

In Ethiopia, few studies have analysed the trend of hydroclimatic variables, including streamflow and rainfall. Conway and Hulme (1993) reported declining annual rainfall over the Blue Nile and Atbara basins, resulting in a reduction of river flows between 1945 and 1984. In contrast, recent investigations by Tesemma et al. (2010), Tekleab et al. (2013) and Gebremicael et al. (2013) agreed that rainfall over the Upper Blue Nile Basin did not show a statistically significant trend for the last 40 years (1964–2005). Despite the fact that the pattern of rainfall remained constant, hydrological flows in the basin showed a heterogeneous trend. Rainy (June to September) and dry (October to February) season flows at the Upper Blue Nile Basin outlet (EI Diem) have significantly increased and decreased, respectively, while the mean annual runoff did not show a statistically significant trend. This implies that trends observed in the river flows may not be attributed to climate change but rather to changes in catchment characteristics. The lack of consensus in the literature may also show that there is still considerable uncertainty about the impact of climate change on the hydrological regimes of the region. The length of the statistical record has a direct implication on the results of the trend analyses and some of the observed discrepancies could be because of applying different periods of time series data. For example, Dixon et al. (2006) investigated the impact of record length on the trend pattern of streamflow in Wales and central England and their results indicated that trends over 50 to 60 years showed a statistically significant increasing trend, while for a medium record length (30–40 years) no such trend was detected. Meanwhile, record lengths less than 25 years tended to show statistically significant increasing trends. This shows that trend analyses are sensitive to the time domain and careful attention should be given during analyses. Moreover, the variability in climatic zone within a basin may also influence the hydrological regimes. Many studies (e.g. Castillo et al., 2003; Yair & Kossovysky, 2002; Li and Sivapalan, 2011) reported that the spatio-temporal runoff generation in semi-arid areas is strongly non-uniform as runoff generation controlling factors are different from that of a humid environment.

With regard to the Tekezē–Atbara river basin, it lacks comprehensive study of the hydro-climatic trends. Seleshi and Zanke (2004) attempted to investigate the pattern of rainfall over the upper part of Tekezē River basin by considering only one climatic station. Their output demonstrated that the amount of rainfall remained constant for the past 40 years (1962–2002). Despite the importance of streamflow to ensure sustainable water resource utilization and food security in the semi-arid regions of the country, long-term trends, change point of flow regimes and their association with climate change are not yet well understood. Therefore, it is important to understand the connections between rainfall and streamflow trends of the basin and establish whether hydrological variability is driven by changes in climate, changes in catchment characteristics or both. This paper is intended to (i) investigate the spatio-temporal variability of rainfall and streamflow in the headwaters of the Tekezē Basin, (ii) identify any abrupt changes if significant trends exist, and (iii) explore the impact of climate change reflected in change in rainfall patterns on the hydrological variability of the basin.

2 Study area descriptions

The study area is the upper part of Tekezē River basin, located in northern Ethiopia between longitude 37.5–39.8° E and latitude 11.5–14.3° N (Fig. 1). The Tekezē River originates in the southern part of the basin near the Simēn Mountains and flows in a northerly direction before turning towards the west flowing into north-eastern Sudan, where the river joins the Atbara River (Zenebe, 2009; Belete, 2007). This basin is one of the major tributaries of the Nile River, which drains an area of 45 694 km^2 at the Embamadre gauging station (Fig. 1). The mean annual flow at this point is $5.4 \times 10^9\ \mathrm{m}^3\,\mathrm{yr}^{-1}$, which is about 66 % of the total annual flow where the Atbara joins the main Nile. The basin is characterized by rugged topography consisting of mountains, highlands and terrains of gentle slopes. The elevation of the basin varies from 834 m a.s.l. at the basin outlet in Embamadre to more than 4528 m a.s.l. in the Simēn Mountains.

The general climate of the basin is semi-arid in the east and north and partly humid in the south, where rainfall ranges from below 400 $\mathrm{mm\,yr}^{-1}$ in the east to more than 1200 $\mathrm{mm\,yr}^{-1}$ in the south (Belete, 2007; Zenebe, 2009). More than 70 % of the total annual rainfall falls in two months (July and August). The variations of rainfall over the basin are mainly associated with the seasonal migration of the inter-tropical convergence zone (ITCZ) and complex topography (Nyssen et al., 2005). The river flow pattern typically follows that of rainfall. Maximum discharge occurs in August, while it ceases completely during the dry season from October to February.

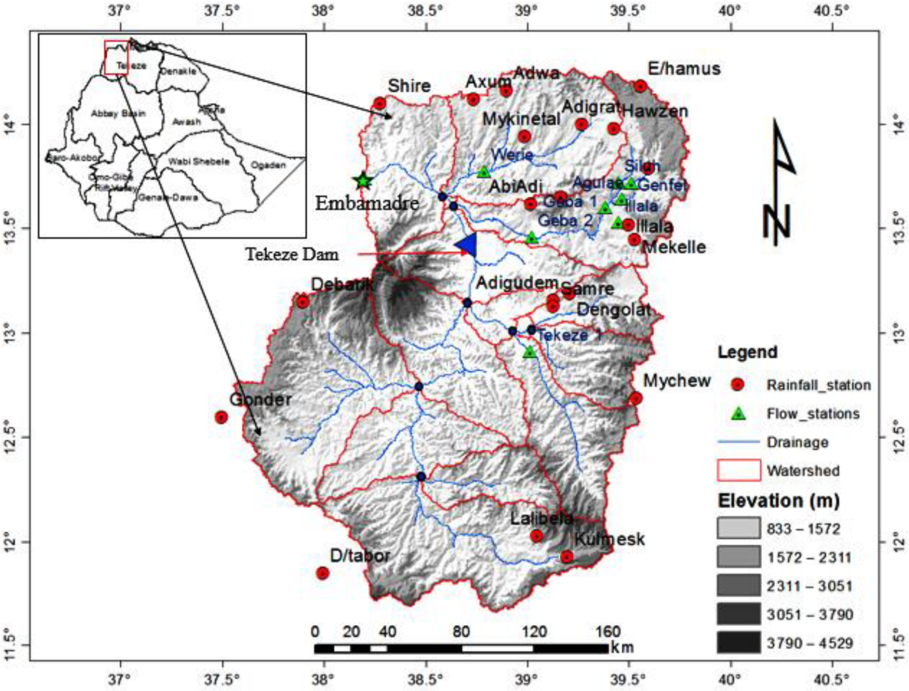

Figure 1. Location and distribution of rainfall and streamflow monitoring stations in the Upper Tekezē–Atbara river basin.

Dominant land use in the basin includes cultivable land (> 70 %), open grassland, sparsely grown woodland, bushes and shrubs, and exposed rocks (Tefera, 2003). This basin is characterized by severe land degradation through deforestation, overgrazing and cultivation on the rugged topography. However, it is also known for its more recent experiences with soil and water conservation (SWC) activities (Alemayouh et al., 2009; Nyssen et al., 2010). Physical SWC structures (Alemayouh et al., 2009; Negusse et al., 2013) and biological SWC measures through plantation and enclosures (Descheemaeker et al., 2006, 2008; Belay et al., 2015) have been practised in the semi-arid parts of the basin. These interventions have been implemented at watershed level for the last three decades. In addition, one large hydropower dam inaugurated in 2009 is found approximately 83 km upstream of the basin outlet (Fig. 1), which may also alter the downstream flow regime.

3 Data and methods

Spatio-temporal datasets of rainfall and streamflow are required for the trend and change-point analyses. These statistical analyses directly depend on the quality and length of the time series data. Therefore, much effort was made to verify the accuracy of the rainfall and streamflow data. These time series data are summarized in Sects. 3.1 and 3.2.

3.1 Rainfall data

For this study, daily rainfall data since 1953 were used from 21 stations located within and surrounding the basin (Fig. 1 and Table 1). These data were provided by the Ethiopian National Meteorological Service Agency. After scrutiny of all stations, only 21 out of more than 75 stations in the basin were considered for further analyses. The length of the records vary from station to station, whilst all gauging stations with at least 30 years of continuous and relatively good quality of observed data were taken into account. A 30-year record is a reasonable minimum for applying statistical trend analyses of rainfall (Love et al., 2010; Longobardi and Villani, 2009).

Rainfall data analyses and validation

Visual inspection, linear and multiple regression analyses between neighbouring stations and other global datasets, including New_LocClim software package (Grieser et al., 2006), Climate Hazards Group InfraRed Precipitation (CHIRPS) (Funk et al., 2014) and the Tropical Rainfall Measuring Mission (TRMM) (Simpson et al., 1988), were applied for data analyses and validation, detecting outliers, filling missing values and checking reliability for all gauging stations. The rainfall datasets were found to be reliable for statistical analyses following screening criteria.

The coefficient of variation in annual rainfall of the basin ranged from 18 % in the southern to 33 % in the eastern and northern parts of the basin. As shown in Table 1, all

Table 1. General information on rainfall stations, latitude and longitude, altitude (Alt.) in metres above sea level (m a.s.l.), mean annual rainfall (mm yr^{-1}), standard deviation (mm yr^{-1}), and percentage of missing data.

Station name	Lat. (°)	Long. (°)	Alt. (m)	Recording period	Analysis period	Mean	SD	CV (%)	Missing data (%)
Mekelle	13.45	39.53	2260	1952–2015	1953–2015	576	141	24	0.0
Mychew	12.69	39.54	2432	1953–2015	1953–2015	697	158	23	6.3
Axum	14.12	38.74	2200	1962–2015	1963–2015	690	159	23	9.4
Gonder	12.60	37.50	2316	1952–2015	1964–2015	1090	195	18	0.0
Adwa	14.16	38.90	1950	1964–2015	1967–2015	705	176	24	7.6
Mykinetal	13.94	38.99	1815	1967–2015	1967–2015	585	129	22	8.1
Shire	14.10	38.28	1920	1963–2015	1968–2015	953	203	21	10.1
Adigrat	14.00	39.27	2470	1970–2015	1970–2015	596	172	29	2.1
Adigudem	13.16	39.13	2100	1975–2015	1971–2015	498	156	31	2.2
E/hamus	14.18	39.56	2700	1971–2015	1971–2015	651	214	33	2.2
Hawzen	13.98	39.43	2255	1971–2015	1971–2015	505	116	23	6.6
Illala	13.52	39.50	2000	1975–2015	1975–2015	563	138	25	4.9
H/Selam	13.65	39.17	2630	1973–2015	1973–2015	685	168	24	0.0
AbiAdi	13.62	39.02	1850	1961–2015	1973–2015	861	246	29	2.3
Samre	13.13	39.13	1920	1967–2015	1978–2015	650	188	29	6.1
D/tabor	11.85	38.00	2969	1974–2015	1974–2015	1502	264	17	2.3
Dengolat	13.19	39.21	1950	1975–2015	1975–2015	617	166	27	2.4
Lalibela	12.03	39.05	2450	1972–2015	1978–2015	789	169	21	5.3
Wukro	13.79	39.60	1995	1962–2015	1985–2015	485	139	29	9.4
Kulmesk	11.93	39.20	2360	1973–2015	1985–2015	668	180	27	3.2
Debarik	13.15	37.90	2850	1955–2015	1984–2015	1104	231	21	6.2

but two stations have a coefficient of variation below 30 %, which is an acceptable limit for data validation (Medvigy and Beauliew, 2012; Sushant et al., 2015). To ensure data continuity and integrity, missing rainfall data of less than 1 year were estimated from global and neighbouring stations, and data gaps larger than 1 year were excluded from the analyses. Based on these data screening and analysis methods, rainfall stations with less than 10 % missing data have been used in the analyses.

Satellite data including CHIRPS and TRMM were used to validate and fill the missing values. Among many rainfall estimates (RFEs) in the area, for example CMORPH, ERA40, CHIRPS and TRMM, the latter two were selected for this study. Both satellite data sources have a relatively high resolution (TRMM 0.25° and CHIRPS 0.05°) and are commonly used in Africa (Shukala et al., 2014; Katsanos et al., 2015). Detailed descriptions of these rainfall products are documented in many publications (e.g. Dinku et al., 2007; Funk et al., 2014; Katsanos et al., 2015; Simpson et al., 1988). Before using them for validation and checking reliability, the rainfall products were first compared directly with observed rainfall of selected stations with good quality data. As the observed rainfall data in the region are sparse and unevenly distributed, the point data were not interpolated into gridded time series. Instead, area-averaged time series of satellite rainfall products around each gauging station ($\sim$ 25 km radius) were used for the comparison. A 25 km radius of area average rainfall was considered to account for the satellite data resolutions as well as to avoid the effect of topography complex on the rainfall estimation. A comparable time period (1998–2015) of the satellite (y) and ground rainfall (x) data were considered for the comparison.

The performance of the satellite products in estimating the amount of rainfall around the gauging stations was evaluated using statistical measures shown in Table 2. Their full descriptions can be found in Toté et al. (2015), Thiemig et al. (2012) and Derin and Yilmaz (2014).

Both CHIRPS and TRMM (3B42v7) satellite products were evaluated against monthly rainfall values from seven observed stations. The performance results show that CHIRPS outperformed TRMM for the majority of stations (Fig. 2). CHIRPS rainfall data showed a good correlation with observed rainfall in the stations. Figure 2 shows N_{SE} for CHIRPS rainfall data were greater in the majority of the stations whilst R_{MAE} were lesser compared to TRMM. This clearly shows that CHIRPS estimated the rainfall closer to the observed rainfall than TRMM. Accordingly, the CHIRPS rainfall data were used for checking reliability and filling missing values of all stations before trend analyses. It has been reported that this product has a better performance in Africa (Funk et al., 2014; Toté et al., 2015). Hessels (2015) compared 10 satellite rainfall products over the Nile Basin, and CHIRPS products performed the best and were recommended for the basin. The likely reason for its better perfor-

Table 2. Statistical indices for accuracy measurement of satellite rainfall products.

Statistical measure	Equation	Best value
Relative mean absolute error (R_{MAE})	$(1/N\sum\lvert(y-x)\rvert/(\overline{x})$	0
Nash–Sutcliffe efficiency (N_{SE})	$1-(\sum(y-x)^2/(\sum(x-\overline{x})^2)$	1
BIAS	$\sum y/\sum x$	1
Pearson correlation coefficient (r)	$\frac{\sum(x-\overline{x})(y-\overline{y})}{\sqrt{(x-\overline{x})^2}\sqrt{(y-\overline{y})^2}}$	1

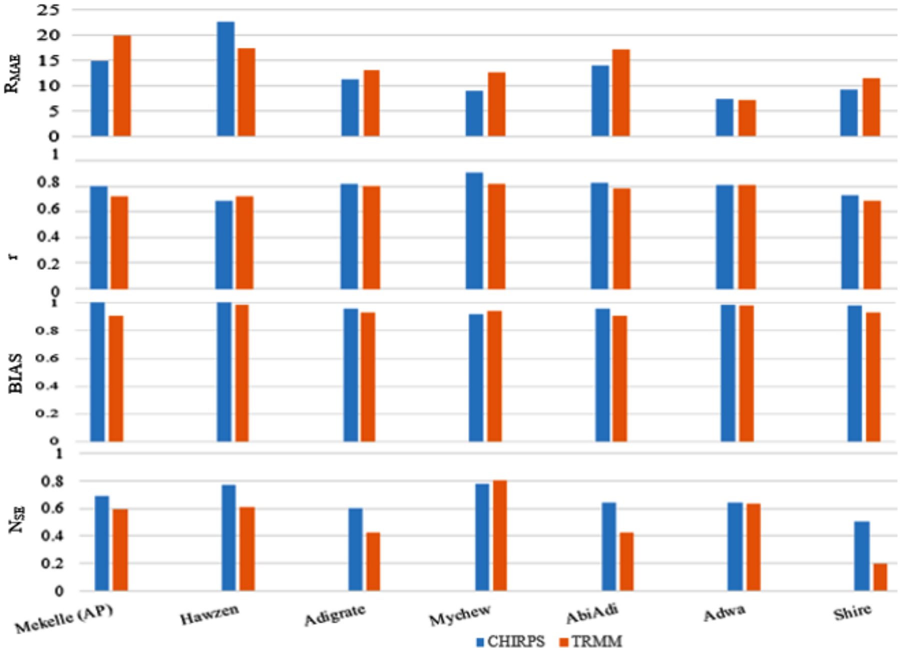

Figure 2. Comparison of satellite rainfall data against measured rainfall data.

mance could be because of its availability at a high resolution of 0.05°.

3.2 Streamflow data

Streamflow data from all gauging stations in the basin were obtained from the Ethiopian Ministry of Water Resources and Energy. Although the recording of flow data over the basin started in the late 1960s, it was discontinued for most of the gauging stations during the civil war in the 1980s. To this effect, only 9 out of the total 39 stations have an extended period of more than 20 years of data and these were used in the analyses. Spatio-temporal trends can be affected by the chosen length of records. A longer period of historical data increases the visibility of dominant trends and the reliability of results from trend analyses, while a shorter period enhances spatial coverage of streamflow by including more representative stations at different parts of the basin. To better account for the spatial variability of streamflow, data spanning more than 20 years can be desirable for trend analyses of streamflow (Abdul Aziz and Burn, 2006; Saraiva-Okello et al., 2015; Abeysingha et al., 2015). The location and general information on all flow stations used are summarized in Fig. 1 and Table 3. The average annual flows of each station indicate that hydrological responses are spatially uneven over the basin. For example, Illala and Werie have higher streamflow per unit area compared to Genfel and Geba 1 tributaries. This is despite there being a large difference in the drainage area (Table 3 and Fig. 1), where approximately the same runoff volume is contributed to the Geba 1 from Genfel and Illala tributaries. Moreover, looking into the drainage area of Geba 2 (4590 km^2) and Werie (1770 km^2), more water is discharged from Werie (5 %) than from Geba 2 (6 %) to the basin outlet (Tekezē 2), which suggests a high variability in hydrological response to catchment characteristics.

As for hydro-meteorological data in the basin, as most basins in Ethiopia are very limited and with many gaps,

Table 3. General information on the hydrological flow monitoring stations.

Station name	Lat.	Long.	Alt.	Catchment area (km^2)	Recording period	Analysis period	Annual average flow (m^3 s^{-1})	Missing data (%)
Siluh	13.85	39.51	2230	967	1973–2015	1973–2015	1.0	4.6
Illala	13.53	39.50	2004	341	1980–2015	1980–2015	0.6	2.8
Genfel	13.80	39.60	1997	733	1992–2015	1992–2015	0.6	2.1
Werie	13.85	39.00	1380	1770	1967–2015	1994–2015	10.1	0.8
Agulae	13.69	39.58	1994	692	1992–2015	1992–2015	1.1	0.3
Geba 1*	13.6	39.38	1748	2445	1967–2015	1990–2015	3.9	4.0
Geba 2*	13.46	39.02	1370	4590	1994–2015	1994–2015	14.2	0.0
Tekezē 1*	12.60	39.19	1490	1002	1994–2015	1994–2015	3.0	3.2
Tekezē 2*	13.74	38.20	845	45 694	1969–2015	1994–2015	219.5	0.0

* Geba 1 and 2 are Geba at Mekelle and Adikumsi, respectively, and Tekezē 1 and 2 are Tekezē at Kulmesk and Embamadre, respectively.

it is critical to carefully screen and check their quality before using them for analyses. Hence, the raw data were visually inspected and screened for typos and outliers. Each station was carefully checked for data consistency by comparison to nearby, upstream and downstream stations. Relationships between neighbouring stations can give preliminary evidence on the reliability of time series data, provided that there is no man-made water storage above the station (Hong et al., 2009). Identified unreliable data were fixed after comparing its upper and lower boundary limits. Furthermore, heterogeneity of the time series data was also detected using the double mass curve and residual mass plot methods. The monthly hydrological flow data were aggregated from the daily data and the seasonal and annual data were calculated from the monthly data. Unreliable data were removed, whilst more stations were included to increase spatial coverage. Missing data (> 2 years) were excluded from the analyses. However, during the peak rainy season, missing data for more than 2 weeks were excluded from the analyses. The reason to exclude only 2 weeks was to minimize untrustworthy data as more than 80 % of the river flow is generated during only two months (July and August).

3.3 Trend analyses method

To identify the trends in rainfall and streamflow, a non-parametric Mann–Kendall (MK; Kendall, 1975) statistical test is applied. The Mann–Kendall test, is a rank based method that has been widely used to detect the trend of hydro-climatic time series data in different parts of the world (e.g. Abdul Aziz and Burn, 2006; Gebremicael et al., 2013; Jones et al., 2015; Návar, 2015; Tekleab et al., 2013; Mohamed and Savenije, 2014; Wang et al., 2015). The procedure of MK testing starts by calculating the MK statistic S using Eq. (1) (Yue et al., 2002).

$$S=\sum_{i=1}^{n=1}\sum_{j=i+1}^{n}\operatorname{sgn}\left(x_j-\mathrm{x}_i\right),\ \text{where}\ \operatorname{sgn}(\theta)=\begin{cases}+1\\0\\-1\end{cases}\text{if}\begin{bmatrix}\theta>0\\\theta=0\\\theta<0\end{bmatrix},\tag{1}$$

where x_j and x_k are the data values in time j and k, respectively, $j > k$, and n is the length of dataset. The normalized test statistics Z of the MK test and the variance VAR(S) were calculated as shown in Eqs. (2) and (3).

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{V(S)}}\\0\\\dfrac{S+1}{\sqrt{V(S)}}\end{cases}\text{if}\begin{bmatrix}S>0\\S=0\\S<0\end{bmatrix},\tag{2}$$

$$V(S)=\frac{1}{18}[n(n-1)(2n+5)],\tag{3}$$

where S and $V(S)$ are the Kendall's statistics and variance, respectively. The MK test calculates Kendall's statistics s, which is the sum of the difference between data points and a measure of associations between two samples (Kendall's τ). The MK test, accepts the null hypothesis if $-Z \le Z_{\mathrm{cr}} \le Z$, where Z_{cr} is critical value of the normalized statistics Z at 5 % confidence level (1.96). Positive and negative values of those parameters (z and s) indicate an "upward trend" and "downward trend", respectively. In order to evaluate the trend results, the Z value combined with the computed two-tailed probability (P) were compared with the user-defined confidence level (5 %) of the standard normal distribution curve. The MK test is commonly used and suitable to identify trends in hydrological data as it is not affected by the distribution, outliers and missing values of time series data (Yue et al., 2002, 2003; Zhang et al., 2008, 2011).

The existence of serial correlation in the time series data may affect trend detection in the non-parametric trend test methods (Masih et al., 2011; Zhang et al., 2011). The trend-free pre-whitening (TFPW) method (Yue et al., 2003) was employed to avoid serial correlations in the data. This method is found to be the most powerful tool to remove a serial correlation time series if it exists (Yue et al., 2003; Burn et al., 2004; Tekleab et al., 2010; Mohamed and Savenije, 2014). The data series was pre-whitened using the formula shown in Eq. (4).

$$Y_1 = Y_t - r_1 \cdot Y_{t-1}, \tag{4}$$

where r_1 is the estimated serial correlation coefficient, Y_t is trended series for time interval t, Y_1 is data series without auto-regressive part and Y_{t-1} is the original time series value. Detailed descriptions of TFPW can be found in literature (e.g. Yue et al., 2003; Burn et al., 2004; Tekleab et al., 2013; Gao et al., 2011). Finally, the MK test was applied to the TFPW data series for analysing the gradual change in the rainfall and streamflow.

3.4 Change-point detection method

To estimate the occurrence of an abrupt change, a non-parametric Pettitt test (Pettitt, 1979) was applied to the TFPW data series. The Pettitt test is a rank-based and distribution-free test for identifying if there is a significant change between cumulative functions before and after a time instant. The Pettitt test considers a sequence of random variables $X_1, X_2, \ldots, X_T$ that can has a change point at τ if X_t for $t, \ldots, \tau$ has common distribution function $f_1(x)$ and X_t for $t = \tau + 1, \ldots, T$ have a common distribution function $f_2(x)$, and $f_1(x) \neq f_2(x)$. The test statistics $K_T = \mathrm{Max}|U_t, T|$, $1 \leq \tau < T$ and associated probability (P) used to test were computed using equations found in Gao et al. (2011). The test was evaluated against a user-defined significance level (5 %), and P values less than 5 % were considered as a statistically significant change in the data series. The 5 % significance level was chosen as it is commonly used in the hydro-climatic trend analyses (e.g. Tekleab et al., 2013; Gebremicael et al., 2013; Saraiva-Okello Okello et al., 2015). This Pettitt technique has been widely used to detect time change points in the hydro-climatic data (e.g. Ma et al., 2008; Love et al., 2010; Gao et al., 2011; Zhang et al., 2011; Gebremicael et al., 2013; Tekleab et al., 2013).

3.5 Hydrological alteration indicators

Temporal and spatial streamflow variability can also be characterized and quantified using hydrologic alteration indicators. The indicators of hydrologic alteration (IHA) software developed by the US Nature Conservancy (Mathews and Richter, 2007) was applied to assess the degree of hydrological alteration. Out of the total 33 IHA parameters, 8 were selected for this study. The selected parameters are magnitude and duration of annual extreme water conditions (e.g. 1-day, 3-day, and 7-day minimum and maximum flows), rate and frequency of water condition changes (e.g. rising rate and falling rate), and magnitude of monthly water conditions (e.g. monthly flows). Such IHA parameters are common in the characterization of hydrological regimes influenced by climate and anthropogenic factors (Tayler et al., 2003; Mathews and Richter, 2007; Masih et al., 2011; Saraiva-Okello et al., 2015). The consistency of those parameters was analysed and compared with the user-defined P values (5 %).

4 Results and discussion

According to NMSA (1996), major seasons in the study area are the rainy season (June–September), dry season (October–February) and short rainy season (March–May). Before detecting trends in precipitation and hydrological flows, serial correlation existence in all datasets was tested at monthly, seasonal and annual scales. Accordingly, 9.1–18 % of the monthly, seasonal and annual data of the rainfall stations were found to have a statistically significant auto-correlation at 95 % confidence level. This indicates that a false significant trend might have appeared in some of the stations when actually there is no trend because of auto-correlation in the data series. Similarly, 3.2–6 % of the monthly and seasonal flows showed statistically significant auto-correlation. It is unclear why the monthly and seasonal fluxes showed stronger autocorrelation than annual. The probable reasons are storage properties in the catchments, unreliable data and missing values (Hirsch and Slake, 1984; Abeysingha et al., 2015). Furthermore, continuous constant observations in the dry months, when river discharges are very low, may have increased the degree of similarity among consecutive observations. To avoid such spurious trend detection, serial correlation problems in all time periods were eliminated using TFPW techniques before trend analyses. Comparison of rainfall and streamflow before and after TFPW at different scales (monthly, seasonal and annual) is presented in Figs. S1 and S2 in the Supplement, respectively.

4.1 Rainfall variability over the basin

The presence of monotonic increasing or decreasing trends in monthly, seasonal and annual rainfall of 21 gauging stations was tested using the MK test. The results for seasonal and annual rainfall are summarized in Table 4. Positive and negative values of Z statistics show increasing and decreasing trends, respectively. Z statistics in bold illustrate statistically significant trends of rainfall. The spatial distribution of observed significant and non-significant trends of annual rainfall over the basin is also given in Fig. 3.

Results of the trend analyses were used to identify if the time series of annual and seasonal rainfall had a statistically significant trend in the last 30–60 years (Table 4). Figure 3 shows the spatial variability of rainfall on an annual scale throughout the basin. Except for two stations (Axum and

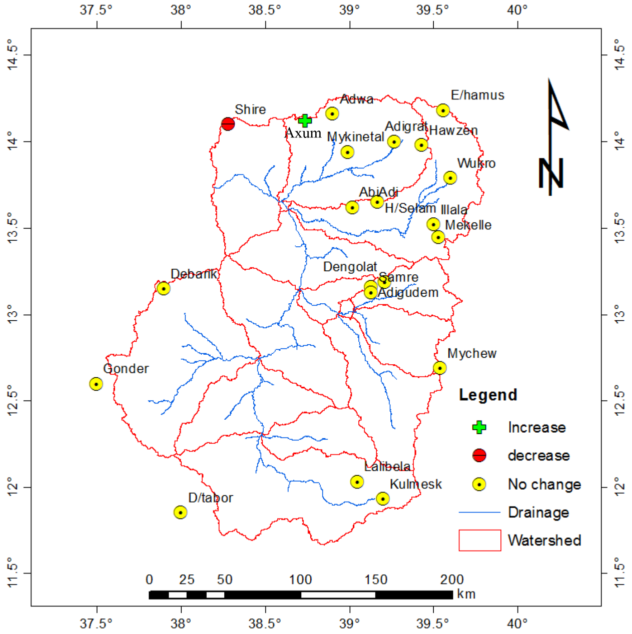

Figure 3. Location of rainfall stations with increasing (+), decreasing (−) and no-change (0) trends on annual rainfall.

Table 4. Summary results of MK and Z statistics on seasonal and annual rainfall trends. Negative (positive) Z value indicates a decreasing (increasing) trend, and statistically significant trends at 5 % confidence level are shown in bold ($Z = \pm 1.96$).

Station/season	Rainy season Jun to Sep	Dry season Oct to Feb	Short rainy Mar to May	annual Jan to Dec
Mekelle (AP)	−1.5	1.7	−1.2	−1.8
Mychew	−1.1	1.0	0.9	−0.7
Axum	1.5	0.3	0.3	**2.5**
Gonder	1.1	−1.7	1.8	0.8
Adwa	**4.6**	1.6	1.1	0.8
Mykinetal	1.7	−1.4	−1.8	−0.3
Shire	1.6	1.4	1.5	**−2.5**
Adigrat	−0.4	1.1	1.1	−0.1
Adigudem	0.0	0.1	−0.8	−0.3
Edagahamus	−0.6	−1.2	−1.7	−1.1
Hawzen	0.7	−1.4	−1.1	−0.4
Illala	1.5	0.3	1.6	1.6
Hagereselam	0.2	−0.3	−1.7	−1.0
AbiAdi	0.9	−1.5	1.9	1.9
Debretabour	1.3	1.5	0.1	1.9
Dengolat	−0.6	0.1	1.7	1.9
Lalibela	0.8	−0.6	−1.1	−1.1
Wukro	−1.4	0.8	1.2	1.6
Kulmesk	0.5	−0.3	0.1	0.1
Debark	0.3	0.4	1.8	1.7
Samre	−0.3	−1.9	−0.3	−0.3

Shire), there are no significant trends in the rainfall of the basin. Both Axum and Shire stations which are located in the north-west part of the basin showed an increasing and decreasing trend, respectively. A possible reason for obtaining different results in these stations is unreliable data, as both stations have the highest percentage of missing data comparing to the remaining stations. However, although not statistically significant, statistical indices of the test revealed a tendency of decreasing rainfall patterns in the eastern and northern part of the basin during the main rainy season and the entire year (Table 4). Meanwhile, there is an increasing tendency in the southern and western parts of the basin for the same timescales. With regard to monthly rainfall, despite some temporal and spatial variability, no dominant trends are found in the majority of the months (see Table S1 in the Supplement).

The Pettitt test was used to identify if there is a breakpoint in the data series. Similar to the MK test, the majority of rainfall stations did not show statistically significant change points at 5 % significance level (see Table S2). For example, change point for annual and seasonal rainfall of some stations can be seen in Fig. 4. Figure 4a and d illustrate that annual rainfall in Mekelle (airport, AP) and Adigrat stations do not show an upward or downward shift in the given time domain. An increasing and decreasing change point of annual and short rainy season (March–May) rainfall in Axum and AbiAdi stations are shown in Fig. 4b and c, respectively.

In general, most of the rainfall stations across the basin did not experience any trend changes at 5 % significance level. The analysis also reveals that even though there is no dominant trend, monthly rainfall over the basin is observed to be more variable compared to the seasonal and annual rainfall (Table S1). One possible reason could be due to intra-seasonal variability of rainfall in which the amount of rainfall receiving during a particular season is the same but varying in distribution among the months within the season. Another possible reason could be topographically induced climate. For example, Bizuneh (2013) noticed that monthly rainfall variability in the Siluh catchment of the Geba Basin is dependent on altitude. Furthermore, observed monthly rainfall variability might be due to large-scale oscillation (e.g. ITCZ) variability rather than long-term climate variability in the basin.

The results of this study are consistent with Seleshi and Zanke (2004) who found no significant trends of rainfall at Mekelle station. Results from neighbouring catchments of similar climate characteristics and application of the same methods of trend analyses have also shown that the pattern of rainfall remained constant for the last 40 years, which is in agreement with our finding (e.g. Tekleab et al., 2013; Gebremicael et al., 2013).

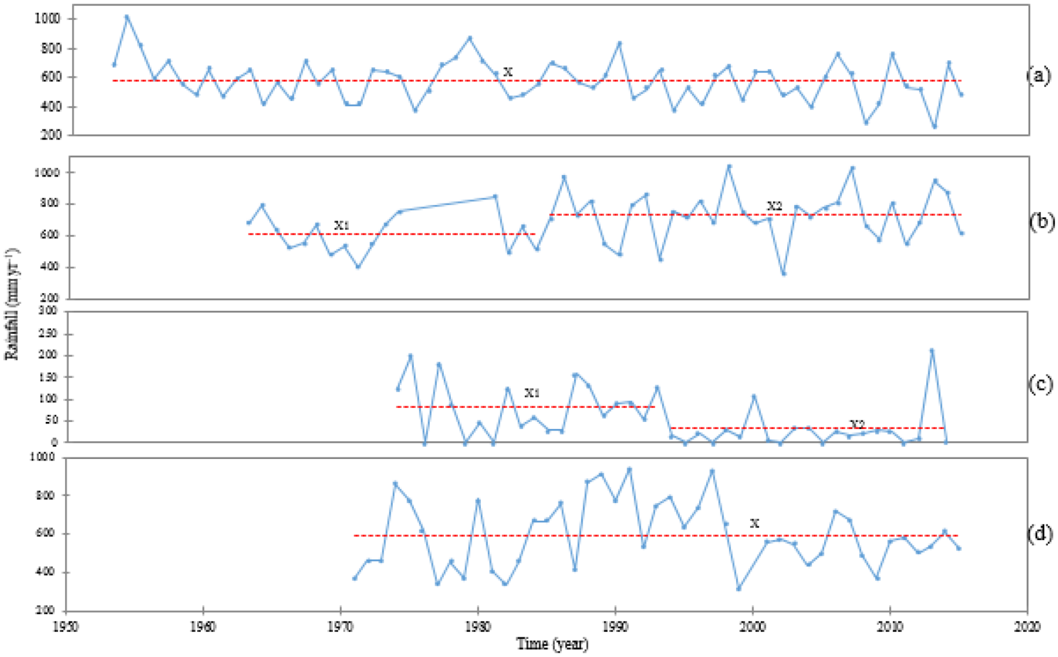

Figure 4. Pettitt homogeneity test of selected rainfall stations **(a)** annual rainfall in Mekelle (AP), **(b)** annual rainfall in Axum, **(c)** short rainy season in AbiAdi and **(d)** annual rainfall in Adigrat. $X1$ and $X2$ are average values of rainfall before and after change point.

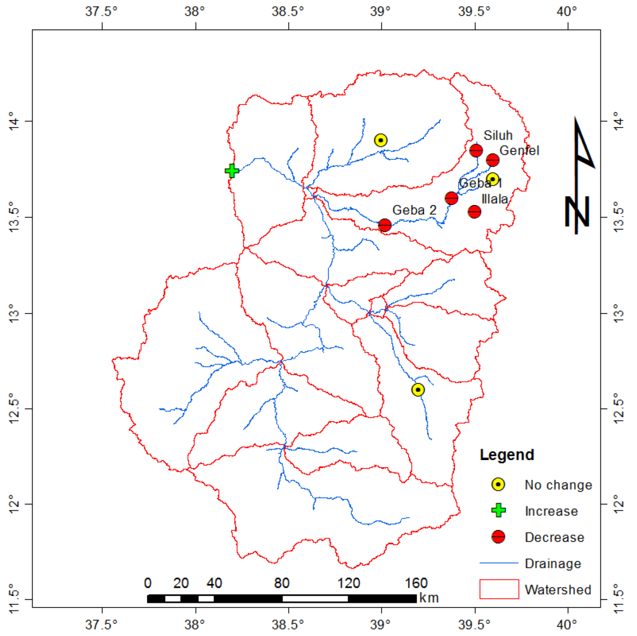

Figure 5. Location of streamflow stations with increasing (+), decreasing (−) and no-change (0) trends on dry season flows.

4.2 Streamflow variability

4.2.1 Long-term trends of streamflow

Streamflow of nine gauging stations (Table 3) was analysed for long-term trend detection using MK and Pettitt test. Table 5 summarizes the results from the MK test, where positive (negative) values of Z statistics associated with the computed probability (P-value) indicate an increasing (decreasing) trends. Furthermore, the observed trends are also presented in Fig. 5 to show the spatial variability of streamflow over the basin. The positive, negative and zero icons in the map indicate an increase, a decrease and no change of dry season streamflow trends across the basin, respectively.

Annual flow patterns exhibited a declining trend in the majority of stations compared to rainfall, which is more pronounced in the eastern part of the basin (Table 5). The change is found to be statistically significant at Siluh, Genfel and Geba stations. Interestingly, although there is a dominant decreasing pattern in the majority of the tributaries, the annual flow at Embamadre station has not significantly changed. Seasonal streamflow of the stations was also analysed to further scrutinize temporal and spatial variability.

The analyses found that a significant decrease of dry season flow has occurred for most stations (Table 5 and Fig. 5). During the short rainy season, a decreasing trend has occurred for five stations, some of these trends being statistically significant. Nevertheless, in the dry and short rainy seasons, flow has significantly increased only at the basin outlet (Embamadre). Streamflow showed a significant increasing trend at Embamadre and a non-significant increasing trend at Kulmesk during the main rainy season. In contrast, a gradual decreasing pattern of flow was recorded in the remaining gauging stations, with this change being significant in four

Table 5. Summary results of MK and Z statistics on streamflow trends. Negative (positive) Z value indicates a decreasing (increasing) trend and statistically significant trends at 5 % confidence level are shown in bold ($Z = \pm 1.96$).

Period	Siluh	Genfel	Agulae	Illala	Werie	Geba 1	Geba 2	Tekezē 1	Tekezē 2
Record length (yr)	1973–2015 43	1992–2015 23	1992–2015 24	1980–2015 36	1994–2015 22	1991–2015 25	1994–2015 21	1994–2015 21	1994–2015 22
Annual	**–4.5**	**–3.1**	−0.9	−0.7	−1.1	**–2.1**	**–2.7**	0.6	1.0
Rainy season	**–3.1**	**–3.2**	−0.4	0.4	0.2	**–2.1**	**–2.8**	1.0	0.1
Short rainy season	**–2.4**	**–3.1**	**–3.5**	**–3.1**	1.1	−1.5	2.7	0.63	**3.9**
Dry season	**–5.0**	**–3.0**	0.3	**–3.0**	−0.9	**–2.2**	**–3.3**	−0.2	**3.4**
Jan	**–5.1**	**–2.3**	−0.7	−2.1	1.4	**–2.7**	**–3.1**	0.4	1.6
Feb	**–4.5**	**–2.6**	−0.2	−1.4	0.8	**–2.8**	−0.4	−0.0	0.8
Mar	**–5.9**	−1.5	−0.5	−1.6	1.2	**–3.3**	−0.2	0.4	1.3
Apr	**–4.0**	**–2.4**	**–4.0**	**–2.9**	0.9	**–2.1**	**–2.6**	0.7	**2.4**
May	**–4.8**	**–2.1**	**–2.6**	**–2.2**	1.3	**–2.1**	−0.3	0.7	**2.3**
Jun	−1.4	−1.9	−0.9	−1.6	0.6	−1.5	−0.2	0.6	1.2
Jul	**–4.7**	**–2.6**	−0.7	−1.0	−0.5	−1.6	−0.4	−0.3	−0.1
Aug	−0.9	**–2.2**	0.8	1.0	−1.2	**–2.0**	**–3.4**	0.3	−1.1
Sep	1.1	−1.6	−0.3	1.5	−0.1	−1.4	−0.4	0.6	0.3
Oct	**–6.7**	−1.8	−0.3	−0.8	**3.8**	**–2.4**	−0.6	0.3	0.9
Nov	**–4.7**	**–4.8**	−1.2	−1.5	0.7	−1.5	−1.1	0.3	0.7
Dec	**–4.7**	**–2.6**	−0.2	−1.5	1.2	**–2.4**	**–3.4**	0.2	0.4

stations (Table 5). Most of the decreasing trends were observed in the eastern and northern parts of the basin where land degradation is believed to be very high compared to the southern and western parts of the basin (Fig. 5). The majority of the gauging stations did not show a consistent positive or negative trend in monthly streamflow. For example, the discharge of Siluh and Genfel stations is characterized by a decreasing trend in most months. In Agulae and Illala catchments, a significant decreasing trend is found in April and May flows while the remaining months observed a decreasing trend that was not statistically significant (Table 5). The combination of Siluh, Genfel and Agulae tributaries at Geba station near Mekelle showed a decreasing trend in all months. Monthly flow patterns of the Upper Tekezē River Basin, the sum of all gauged (Table 3) and ungauged tributaries at Embamadre station, revealed a significantly increasing trend in April and May while all other months remained unchanged (Table 5).

The Pettitt test was also applied to identify an abrupt change of streamflow in the catchments. The change points of annual and seasonal flow for selected stations are shown in Fig. 6. For the annual flow, stations did not show consistent shifts across all stations. For example, annual flows in Siluh and Geba catchments shifted downward after 1992 and 2002, respectively, while no significant abrupt change was observed in Genfel and Tekezē at Embamadre despite strong monthly and seasonal variability (Fig. 6). Change points of seasonal flow for the same stations confirmed an abrupt change in the downward and upward directions (Fig. 6). Dry and short rainy season flows in all stations except at the basin outlet showed significant downward shifts since the early 2000s. Conversely, an abrupt increase in streamflow has occurred at the basin outlet for the same seasons. The Pettitt test has also shown that hydrological flows during the rainy season remained constant for most stations (Fig. 6).

In summary, most stations exhibited a statistically significant change during the short rainy season (five stations) and dry season (six stations). Similarly, trends in the main rainy season and annual flow showed a significant change in three to four of the stations. Several stations exhibited a change point of monthly streamflow (see Fig. S3). Both upward and downward shifts in streamflow were observed in many stations for the months of January, April, May and August (Fig. S3). However, there was no dominant (increasing or decreasing) trend across the basin. For example, change points of monthly (January, April, May and August) streamflow is observed in Siluh catchment (Fig. S3). A downward shift of monthly streamflow has occurred since 1996. The monthly streamflow of Siluh and Geba catchments has significantly declined starting from 1996 and 2004, respectively. In contrast, an upward shift of monthly streamflow was observed at Embamadre for January, April and May, which became significant after 2009.

Interestingly, some of the trends in the upper catchments counterbalance each other when combined in the downstream stations. For example, negative trends during the short rainy season in Siluh, Genfel and Agulae cancelled out when combined at Geba near Mekelle. A remarkable result was

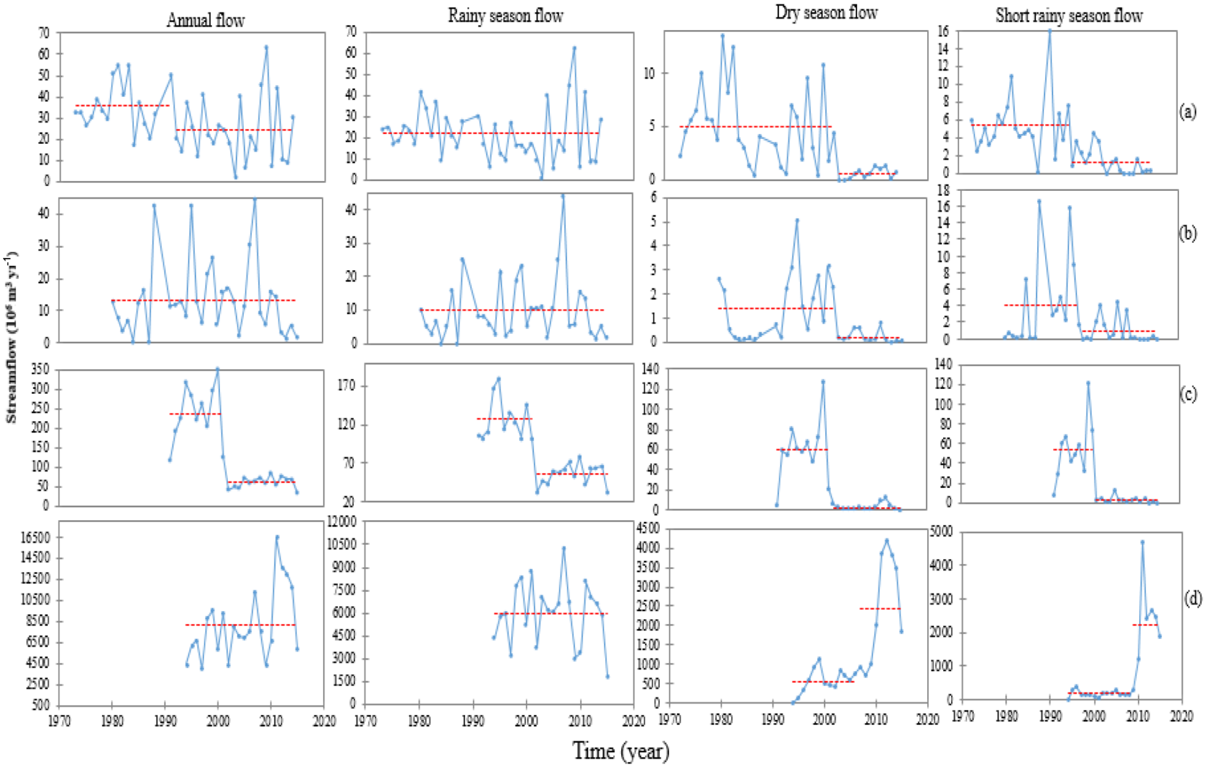

Figure 6. Annual and seasonal streamflow abrupt changes as determined by Pettitt test at **(a)** Siluh, **(b)** Illala, **(c)** Geba 1 and **(d)** Embamadre.

that, although the majority of stations in the upper catchments showed a declining pattern of streamflow, the entire basin flows at the outlet did not show a negative trend. The significant increasing trend during the dry and short rainy season at this station is most likely due to the construction in 2009 of Tekezē hydropower dam, located 83 km upstream of the station. Change in land use and/or land cover from ungauged catchments of the basin might also have contributed to increasing the flow at this station, as this basin is known for its severe land degradation.

The above results are in agreement with previous local studies (e.g. Abraha, 2014; Bizuneh, 2013; Zenebe, 2009), which found strong variability of streamflows in different sub-catchments of the basin. Compared to studies in the neighbouring basin (Upper Blue Nile) by Gebremicael et al. (2013) and Tessema et al. (2010) (at four and three stations, respectively), who found a significant increasing trend of streamflow in short rainy, main rainy, annual flows and a decreasing trend in the dry season flow, the Tekezē basin (particularly in the semi-arid parts of the basin) experienced a significant decreasing trend and high variability of streamflow. This variability is expected as land degradation (e.g. deforestation, over cultivation and grazing) in Tekezē basin is more pronounced than other basins in the country (Awulachew et al., 2007; Gebrehiwot et al., 2011; Gebreyohannes et al., 2013; Yazew, 2005; Zenebe, 2009).

4.2.2 Hydrological alteration indicators

Although the previous analyses showed the long-term trends of rainfall and streamflow in the Upper Tekezē basin, it could not address the short-period fluctuations of the hydrology within the catchment, and whether this can explain some of the results given above. The magnitude and duration of annual extreme conditions were analysed using six IHA parameters (1-day, 3-day and 7-day annual minima and maxima). Results from these extreme conditions indicate a dominant significant decreasing trend in both minimum and maximum daily flows (Table 6). On the other hand, a significant increasing trend of the minimum flow is detected at Embamadre station.

The trends in the rate and frequency of changes in hydrological conditions were also explored using rise and fall rate parameters. Accordingly, the rising rate of daily flow of all stations remained constant while the daily falling rate has significantly increased in the tributaries and decreased in the basin outlet. It can be seen that the trend of minimum flows, described by 1-day, 3-day and 7-day data, is consistent with the trend of monthly and seasonal flows. Moreover, the IHA change-point analyses have also shown shifts in minimum and maximum flow during the dry and wet seasons of the catchments. The extreme 1-day and 7-day minimum and maximum flows significantly shifted downward at the Siluh and Geba catchments. In the Tekezē at Embamadre station,

Table 6. Summary results of MK and Z statistics on IHA trends. Negative (positive) Z value indicates a decreasing (increasing) trend and statistically significant trends at 5 % confidence level are shown in bold ($Z = \pm 1.96$).

IHA parameters	Siluh	Genfel	Agulae	Illala	Werie	Geba 1	Geba 2	Tekezē 1	Tekezē 2
Record length (yr)	1973–2015 43	1992–2015 23	1992–2015 24	1980–2015 36	1994–2015 22	1990–2015 25	1994–2015 21	1994–2015 21	1994–2015 22
1-day minimum	**–4.3**	**–3.2**	−0.7	**–3.4**	0.8	**–3.6**	**–3.8**	−0.6	**2.8**
3-day minimum	**–3.5**	**–4.2**	−0.8	**–3.6**	0.8	**–3.4**	**–3.8**	−0.5	**2.2**
7-day minimum	**–3.5**	**–3.5**	−1.3	**–3.1**	0.7	**–3.9**	**–3.5**	−0.6	**2.1**
1-day maximum	**–5.7**	−1.0	−0.1	0.7	−1.3	**–2.7**	−1.0	0.8	−1.0
3-day maximum	**–5.5**	−1.3	−0.7	0.7	−0.9	**–2.6**	−0.8	−0.1	−1.5
7-day maximum	**–6.4**	**–2.2**	−0.4	0.1	−1.3	**–2.4**	−0.7	−0.6	−1.2
Rise rate	−1.1	−0.4	−1.3	1.0	1.2	−1.5	−1.3	1.0	−0.3
Fall rate	0.8	2.3	3.9	1.6	1.4	2.8	0.8	−2.3	−3.8

the 1-day and 7-day minimum flows significantly increased around 2003, but 1-day and 7-day maximum flows remained unchanged. Illala catchment experienced a decrease of the 1-day minimum and an increase in the 1-day maximum annual flows with change points at around 2000 and 1995, respectively. Extreme high flows characterized by the 1-day and 7-day annual and maximum flows did not significantly change at the basin outlet which may be due to homogenization of the low flow and peak flow hydrograph after the construction of Tekezē hydropower dam above the station (see Sect. 4.2.1)

4.2.3 Drivers for streamflow variabilities

Climatic conditions, in particular rainfall, as well as human activities in a catchment are the most important factors influencing the hydrological variability of streams. In this study, temporal and spatial analyses of rainfall from both MK and Pettitt tests showed that rainfall over the basin did not significantly change during the period of analyses. Streamflow, in contrast, did exhibit a strong temporal and spatial variability in the basin. This suggests that the change in hydrological flow is not significantly influenced by rainfall. The timing of observed trends in streamflow is not uniform. This may indicate that the impact of human interference and physiographic characteristics differ from sub-catchment to sub-catchment. Trend analyses are sensitive to the time domain as different results can be obtained for different time periods. In this study, however, change points occurred at different times in most of the sub-catchments, even for the same time domain (e.g. Genfel and Agulae). This implies that the effect of changes in the underlying surface characteristics could be the physical mechanism behind those variations. Human interventions expressed in terms of water abstraction, implementation of large-scale soil and water conservation, deforestation, and afforestation in the upstream catchments are the more likely driving forces of changes in the flow regimes, rather than climatic conditions. For example, Nyssen et al. (2005) and Belay et al. (2015 reported that a strong decrease of forest and bushland has occurred in favour of cultivable and grazing lands from the 1960s to early 1990s. However, the rate of deforestation and land degradation in most parts of the basin has slowed down and even started to recover by increasing the coverage of vegetation from the late 1990s onwards (Nyssen et al., 2010). The conversion of vegetation cover into agricultural land has increased runoff by 72 % and decreased dry season flow by 32 % in some parts of the basin. Studies in neighbouring basins (e.g. Upper Blue Nile) also confirmed that conversion of vegetation cover into agriculture and bare land has caused an increase of surface runoff and decrease of base flow up to 75 and 50 %, respectively.

Increasing water abstractions, particularly in the semi-arid catchments of the basin, might have caused the decline of streamflow during dry and small rainy seasons. Several studies (e.g. Alemayehu et al., 2009; Kifle, 2015; Nyssen et al., 2010) have shown that surface and shallow groundwater development and abstraction for irrigation have significantly increased since the mid-2000s, after implementation of intensive catchment management programmes. Moreover, a strong monotonic trend in streamflow without a significant change in rainfall during the rainy season could be attributed to the large-scale soil and water conservation interventions in the upstream watersheds. For example, Nyssen et al. (2010) and Abraha (2014) reported that integrated catchment management and land use change have significantly reduced streamflow in Geba catchment. Soil and water conservation interventions have significantly increased the availability of groundwater at smaller watershed levels (Alemayehu et al., 2009; Negusse et al., 2013). All these studies are consistent with our findings that observed streamflow alterations in the basin are most likely the result of upper-catchment interventions rather than changing patterns of rainfall. Quantifying the impacts of such factors at a large scale is beyond the scope of this study, and further investigations should be conducted to study the effect of anthropogenic factors on streamflow variability and change at different scales.

It is also essential to point out some limitations in this study. The absence of common records of rainfall and streamflow data, limited coverage of streamflow time series data across the basin, and data gaps in the peak flow period are the major limitations that may have increased uncertainties in the trend analyses. The length of the record period used for the trend analyses of rainfall and streamflow varied between 31–63 and 20–43 years, respectively. Analyses using these different record lengths of data may introduce some discrepancy in the analyses.

5 Conclusion and recommendations

This study presents a detailed statistical analysis on the existence of trends and point changes of rainfall and streamflow in the Upper Tekezē River basin. The analyses were carried out for 21 rainfall and 9 streamflow monitoring stations. Those stations were selected based on the availability and quality of data from 39 streamflow and more than 75 rainfall stations available in the basin. Linkages between the trends in rainfall and streamflow across the whole basin were carefully examined at different scales. Following these analyses the main driving force for streamflow variability over the basin is deduced.

Rainfall over the basin has remained constant in the last four decades. A total of 19 out of the 21 tested stations experienced neither increasing nor decreasing trends during the dry season, short rainy season, main rainy season or at the annual level at 95 % confidence level. Furthermore, the result of this study clearly showed that monthly rainfall in the majority of the stations experienced high spatial variability compared to the seasonal and annual timescales. In contrast, trend analyses of different hydrological variables showed that streamflow in most stations has changed significantly. A decreasing trend in the dry season, short season, main rainy season and annual totals is dominant in six out of the nine stations, located in the semi-arid areas of the basin. The significant decreasing pattern of streamflow is observed in the eastern and northern part of the basin where land degradation is very high. Only one station, located at the basin outlet, exhibited a significant positive trend during both the dry and short rainy seasons. The different trend in this station is likely due to the construction of the Tekezē hydropower dam in 2009. The remaining two out of the nine stations stayed constant in all seasons. Findings from both MK and Pettitt tests are consistent in all seasons and stations, but the timing of change points is different for most stations. This could imply that the level of human interference and physiographic characteristics is varying from sub-catchment to sub-catchment, and hence the differences in runoff generation response to catchment characteristics.

Surprisingly, our results shows that there is no link between the trends in rainfall and streamflow in the basin. This suggests that the change in streamflow is influenced by factors other than rainfall. A weak relationship between rainfall and streamflow leads to the conclusion that the significant trends in streamflow could be due to significant changes in catchment characteristics over time, including change in land use and/or land cover, catchment management interventions, and water abstractions in the upstream. This was also supported by a few existing studies, as discussed in Sect. 4.2.3.

The findings from this study are useful as a prerequisite for studying the effects of catchment management dynamics on the hydrological variabilities. Statistical trend analyses investigate only the trend of historical data without being able to identify the causes of those trends. Therefore, further investigations are needed to verify and quantify the hydrological changes shown in statistical tests by identifying the physical mechanisms behind those changes.

The Supplement related to this article is available online at doi:10.5194/hess-21-2127-2017-supplement.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This study was carried out with the support of the Netherland Fellowship Programme (NUFFIC) and Tigray Agricultural Research Institute (TARI). The authors would like to thank the Ethiopian National Meteorological Agency for providing the weather data and Ethiopian Ministry of Water Resources for providing hydrological data of the study area. The authors would like to thank the two anonymous reviewers for their significant role in improving the quality of this paper.

Edited by: G. Jewitt
Reviewed by: two anonymous referees

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