Trend and Variability Analysis of Rainfall & Stream Flow Series at Tekeze River Basin, Ethiopia

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Abstract: Tekeze River Basin is a trans-boundary river basin in the North-West part of Ethiopia and is a data scarce basin with limited number of gauging stations. The natural flow regime and the spatial and temporal variability of the Basin are poorly understood and remain poorly described. The lack of data and information has resulted in a limited knowledgebase for water resource planning and management decisions. Thus, there is an opportunity to improve water management, if it can be underpinned by a better scientific understanding of the rainfall variability and streamflow availability and variability in the basin. This research is carried out using Mann-Kendall, Pettit test and Indicators of Hydrologic Alteration software to determine the potential trend of rainfall and assess its significance with stream flow variability in Tekeze River Basin. Trend in mean monthly rainfall data shows increasing trends in the Eastern part of the Basin where as decreasing trend for Western part of the basin. Indicators of Hydrologic Alteration (IHA) also used to evaluate hydrologic variables and trends generated from daily streamflow data at Embamadre. The significant results in the streams downstream of Tekeze reservoir had increased minimum flow, decreased maximum flows, increased fall rates, decreased summer monthly flow and decreased high pulse rates. Generally investigation of trends in the hydro-climatic variables of Tekeze River Basin revealed a number of significant trends, both increasing and decreasing. The observed changes were non uniform in term of their spatio-temporal prevalence in the basin.

Index Terms*: IHA, Mann-Kendall test, Rainfall variability, Streamflow variability, Tekeze River Basin, Trend analysis*

1. Introduction

Climate is the most important driving parameter that causes year-to-year variability in socio-economic and environmental systems including the availability of water resources. It affects the development and planning of water resources schemes such as hydropower production, flood prevention and control, drought management, etc. Rainfall is vital natural resources on the earth which can be seen as the major backbone of all the water resources, and is one of the key climatic variables that affect both the spatial and temporal pattern of water variability. Streamflow is also a prerequisite for planning and management of water resources such as the design of dams and hydropower plants, assessment of water availability for irrigation and other water uses, assessment of flood and drought risks and ecological health of a river system.

From the review of literature it is evident that several studies [1] - [3] have been undertaken to characterize trends in rainfall and stream flow at various locations across the globe.

Climate variability appears to have a very marked effect on many hydrological series [4]. These studies have adopted several statistical techniques to quantify increasing or decreasing trends in annual and monthly rainfall and stream flow. Most commonly adopted trend detection techniques used in this research were Mann Kendall, Petit test and IHA. According to the study by Gebremichael [5] the historical hydro-meteorological data analysis, Upper Blue Nile Basin showed a high variability in the river flows and rainfall pattern. Even with good number of researches [6] – [9] on various hydrological and environmental issues in the Upper Blue Nile Basin, very little work has been done to investigate variability of rainfall and stream flow in the Tekeze basin part of Nile River basin. Thus, there is an urgent need to understand temporal and spatial variation of rainfall and stream flow, and its controlling factors in the Tekeze River Basin as the government of Ethiopia planned to construct more hydropower dams and irrigation projects in this basin.

Therefore, the goal of this research is to determine whether or not there have been significant changes in rainfall and streamflow during the time of record and employ popular statistical techniques to characterize trends in monthly rainfall and daily stream flow to provide some information to the government and community for future planned hydropower dams and irrigation projects in the basin.

2. Materials and Methods

2.1 Study Area

Tekeze River basin is situated in the North-West part of Ethiopia between 11°40' to 15°12' N, and 36°30' to 39°50'E begins at the springs near Lalibela in the central Ethiopian Highlands near Mount Qachen within Lasta, Wollo and shared with Ethiopia and Eritrea after entering northeastern Sudan joins the Atbarah River a tributary of the Nile. The basin has a total drainage area of 86,510 km^2; of which 82,350 Km^2 (95.19%) in Ethiopia covering parts of the Amhara and Tigray regional states and relatively small part of the basin 4,160 km^2 (4.81%) is situated in Eritrea. The River commences from the highlands of Wollo and Gonder in the south and drains central, southern and small portion of the western Tigray and Northern Gonder westward to the Nile. The river basin has a lowest elevation of 536 m in low lands of Metema area and a highest elevation of 4517 m at Semen Mountains.

The climate of this basin can be divided into two: the west region of the Simien Mountains with wet season and the east region with dry (small rainy) and wet (main rainy) seasons. The mean temperatures in the basin vary from 10^{0}C in the Simien Mountains to 22^{0}C in the highlands and to 26^{0}C in the lowlands. Also the minimum and maximum temperature ranges are 3-21^{0}C in the Simien Mountains and 19-43^{0}C in the lowlands areas. Rainfall decreases from west to east from 1,200 to 600mm. The mean annual rainfall is 600mm in the lowlands and 1,300mm in the Simien Mountains.

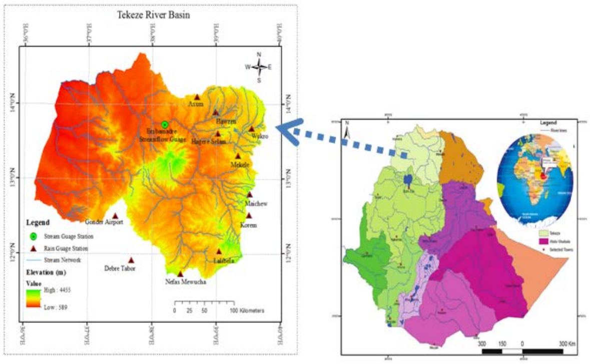


Fig 1 Map of the location of the study area with eleven rainfall station and one stream gauging station

2.2 Data and Analysis

2.2.1 Rainfall

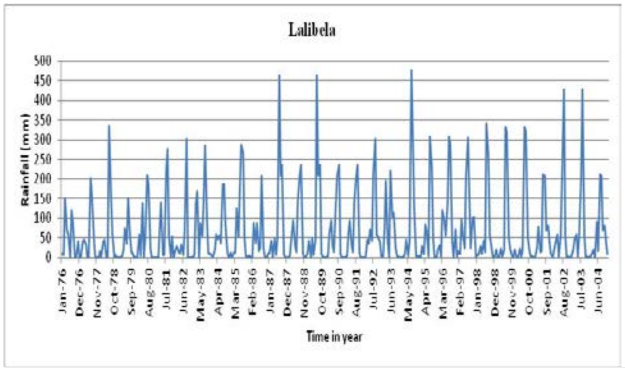
In this study, the longest records of daily rainfall data corresponding to eleven selected stations (Fig1) for Tekeze River Basin which are collected from the Ethiopian National Metrological Service Agency were analyzed to determine whether there is evidence of specific trends in the characteristics of monthly rainfall events in the basin. The period of record (Table 1) was started from 1953 to 2013 with varying record length. The length of record varies due to differences in site establishment and data gaps due to civil war in 1980s in the area. To check on the spatial coherence of the variability results across the study area, a period of not less than 20 years over which each station had rainfall data was considered.

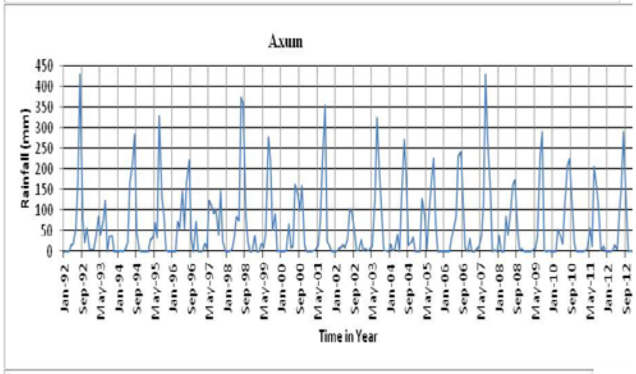
A number of potential data problems, for instance missing values, data entry errors, outliers, etc., were solved by careful inspection. The data were screened and comparisons between stations were made using the statistical metrics mean, standard deviation (STD), skewness (Cs), and actual excess kurtosis (Ku). The spatial and temporal heterogeneity in rainfall characterised using statistical analysis and annual anomalies. The data was sorted and arranged in Excel then XLSTAT2015 Mann-Kendall test [10], [11] was employed to analyze the trends in both rainfalls for all the eleven stations using the monthly data of period 1953 to 2013. The test is to identify whether or not a statistically significant decreasing or increasing trends or none could be found in a data set. The Pettitt test [12] is used to detect abrupt changes in the time series.

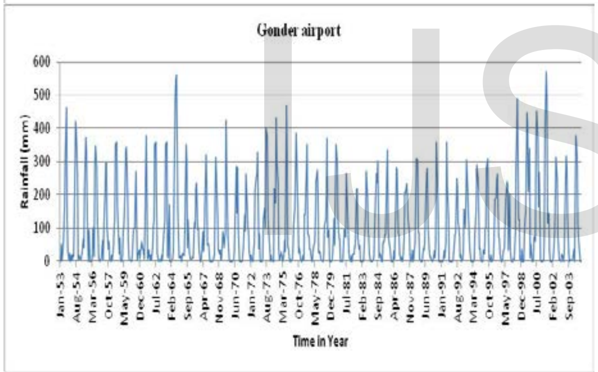
Table 1 Ggeographic conditions and mean annual rainfall statistics for study stations

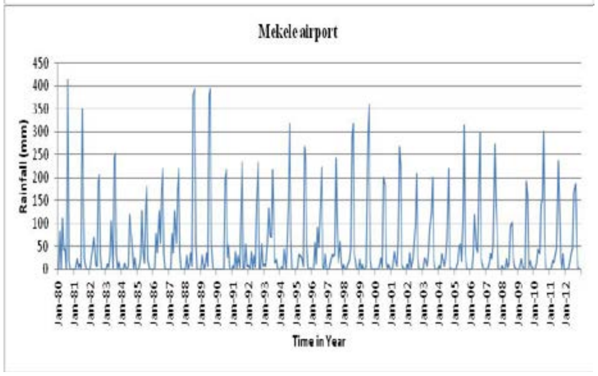
Station	Lat (o)	Long (o)	Altitude (m)	From	To	Mean Annual (mm)	STD	Cs	Ku
Axum				1992	2012	723.94	88.24	1.91	3.47
Debre Tabor	11.53	38.02	2690	1988	2013	1439.04	148.15	1.32	0.65
Gonder Air port	12.33	38.02	1967	1953	2004	1175.18	120.62	1.41	1.26
Hager Selam	13.39	39.09	2000	1994	2012	692.49	82.41	1.90	3.50
Hawzen	13.58	39.26	2242	1971	2012	531.90	66.91	2.07	3.90
Korem	12.31	39.31	3000	1985	2012	980.50	103.00	1.68	2.14
Lalibela	12.31	39.03	2500	1976	2004	799.07	96.12	1.93	3.47
Maichew	12.48	39.32	2400	1971	2012	733.03	72.05	1.47	1.58
Mekele Airport	13.3	39.29	2070	1980	2012	603.68	84.18	2.21	4.47
Nefas Mewucha	11.44	38.27	3000	1986	2004	1103.41	113.82	1.90	4.13
Wukro	13.46	39.36	2070	1992	2012	581.29	90.07	2.41	5.44

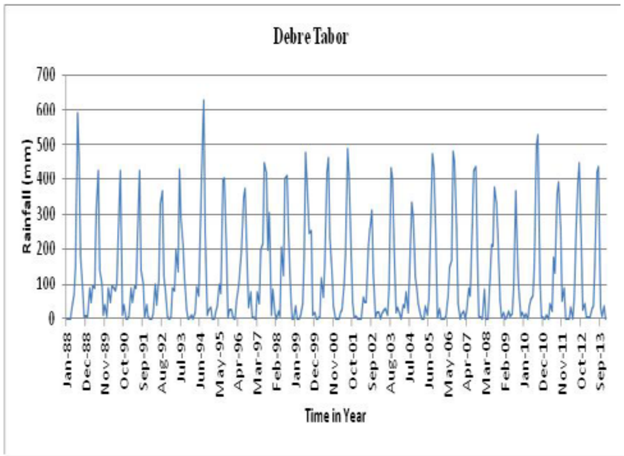
The yearly time series of the rainfall for different stations considered for the analysis are plotted. From (Fig 2) below the variation of yearly rainfall can be easily seen.











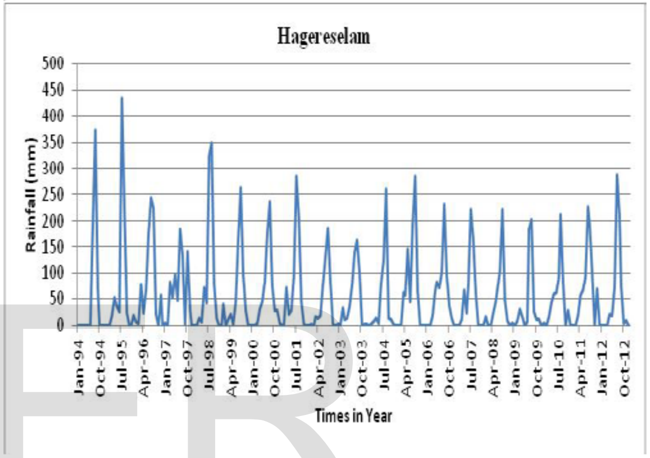


Fig 2 Yearly rainfall analyses at various Tekeze Basin meteorological stations

2.2.2 Trends detection test

Mann-Kendall Test: is used for detection of statistically significant trend in variables like rainfall and streamflow. These are extremely important parameters for watershed modelling, studying catchment characteristics which are very important to determine water resources planning strategies in the long term for any region. The Mann-Kendall (MK) trend test was used because it is simple, robust, can cope with missing values, and the data need not conform to any particular distribution [10], [11]. This method is very essential as it has no assumption were made in the data to be tested. Letting X1, X2,…,Xn be a sequence of measurements over a time, Mann proposed to test the null hypothesis, Ho, that the data come from a population where the random variables are independent and identically distributed.

The alternative hypothesis H1 is that the data follow a monotonic trend over time (that there is trend). Using the XLSTAT 2015 plug-in of Microsoft excel, the monthly percentage contributions of rainfall over years were subjected to the MK trend test shown in Equation (1). Under Ho, the Mann-Kendall test statistics is given by:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1} sign(x_j - x_k)$$

(1)

$$sign(x_j - x_k) = \begin{cases} 1 if x_j - x_k \succ 0 \\ 0 if x_j - x_k = 0 \\ -1 if x_j - x_k \prec 0 \end{cases}$$

(2)

Where: x1, x2 …..xn represent n data points, *xj* represents the data point at time *j* and *S* is the Mann-Kendall statistic. Tau is estimated as:

$$\tau = \frac{2S}{n(n-1)}$$

(3)

The variance of (S) for independent and identically distributed random variables with no tied data and the standardized MK statistic Z follows the standard normal distribution with mean of zero and variance of one. The variance VAR(S) and Z are computed using equation (4) and (5), respectively. The trend results in this study have been evaluated at 5% significant level. This implies that the null hypothesis is rejected when *Z* > 1.96 in equation (5). Where, Z is the standard normal variate.

$$VAR(S) = \frac{n(n-1)(2n+5)}{18} \qquad \textbf{(4)}$$

The presence of a statistically significant trend is evaluated using the Z value. A positive Z indicates an increasing trend, while a negative value indicates a decreasing trend.

$$Z = \begin{cases} \frac{s-1}{\sqrt{VAR}} if s \succ 0 \\ 0 if s = 0 \\ \frac{s+1}{\sqrt{VAR}} s \prec 0 \end{cases} \qquad \textbf{(5)}$$

Change point detection: Pettitt test [12] is an approximation for a sequence of random variables of the non-parametric method, has been used in this study and helps to indicate where possible change points are (P > 0.8). The Pettitt test only detects the time of a change point, but a t-test was always applied to check the significance of the trend. A significance level of 5% has been applied in this study.

The approximate significance probability (P) for a change point is defined by Equation (6):

$$P = 1 - \rho \qquad \textbf{(6)}$$

Where: *P* is the probability of detecting the point of change and *ρ* is the existence of significant change point.

The ρ -value (two-tailed) has been computed in this study using XLSTAT software with 10,000 Monte Carlo simulations at 99% confidence interval for checking the data homogeneity.

2.2.3 Streamflow

There are more Streamflow gauging stations in Tekeze Basin tributaries obtained from the Department of Hydrology – Ethiopian Ministry of Water, Irrigation and Electricity. A long time series of flow data was not available in most of the stations. The minimum length of streamflow record is 21 years (1994-2014) at Embamadre and less than 15 years (1998-2014) for the remaining stations. Based on the quality of the data, time series length, influence of infrastructure (dams) and spatial distribution, Embamadre station was selected for detailed analysis. The temporal resolution of data available is daily.

The data quality control and homogeneity tests like missing data were examined using [13] IHA software. The recommended length is at least twenty years of daily records for trend analysis [14]. The data collected from Tekeze basin station which have such problems were not used in this research.

The US Nature Conservancy developed a statistical software program known as the Indicators of Hydrologic Alteration (IHA) for assessing the degree to which human activities have changed flow regimes [15]. Many studies successfully applied the methodology of IHA; in order to assess impacts on streamflow caused by anthropogenic drivers [13] and [16] - [17]. An analysis of the indicators of hydrologic alteration (Table 2) was conducted in Tekeze Basin to identify patterns and trends of the streamflow record (a single period analysis for the entire time series and for the period of 1994–2008), as well as to assess the impact of infrastructure on the streamflow two-period analysis, before (1994-2008) and after (2009-2014) the major infrastructure development.

The IHA uses ***daily*** data for its calculations. The IHA statistics will be meaningful only when calculated for a sufficiently long hydrologic record. When Taylor [16] tested the impact of different record lengths on IHA output statistics for a highly variable South African river, they found that for some IHA parameters 20 years was sufficient to account for natural climatic variability, but for others 35 or more years of data were needed. In sum, while 20 years should be considered a good baseline requirement for the amount of data needed. IHA parameters can be calculated using parametric (mean/standard deviation) or nonparametric (median and percentile) statistics. For most situations non-parametric statistics are a better choice, because of the skewed (non-normal) nature of many hydrologic datasets (a key assumption of parametric statistics is that the data are normally distributed).

Table 2 Hydrologic parameters used in the range of variability approach (Richter et al., 1996)

Indicators of Hydrologic alteration group	Regime Characteristics	Hydrological Parameters
Group 1: Magnitude of monthly water conditions	Magnitude timing	Mean or Median value for each Calendar month
Group 2: Magnitude and duration of annual extreme water condition	Magnitude duration	Annual minima and maxima based on1, 3, 7, 30 ,and 90 day means
Group 3: Timing of annual extreme water condition	Timing	Julian date of each annual 1 day maximum and minimum
Group 4: Frequency and duration of high/low pulses	Frequency and duration	No of high and low pulses each year Mean duration of high and low pulses with in each day
Group 5: Rate/frequency of water condition change	Rate of change of frequency	Mean of all positive and negative differences between consecutive daily values No of rises and falls

3. Result and Discussion

3.1 Rainfall Variability

Preliminary Analysis: this study included computing the mean, standard deviation, coefficient of skewness and coefficient of kurtosis in the annual rainfall time series for Tekeze River Basin in each station. The mean annual rainfall varied between 581.29mm in the Northern part of the Tekeze River basin (Wukro) and 1439.04mm in the Southern part (Nefas Mewucha) of this basin. Also the coefficient of skewness varied from 1.47 to 2.41; kurtosis varied between 0.65 and 5.44. For time series data to be considered normally distributed, the coefficient of skewness and kurtosis must be equal to 0 and 3, respectively. (Table 1) indicates, therefore, that the data are positively skewed and not normally distributed.

Mann-Kendall test: XLSTAT2015 was applied on a monthly time scale to detect trends in the rainfall series at different stations. Referring to the station provided in (Table 3 and Fig. 3), the results of the MK test for the eleven rainfall stations showed that a mix of positive and negative trends at different stations, generally the trends are not significant at monthly scale for the majority of investigated climate stations. Significant positive trends were detected in most of the stations; however, for some stations values statistically significant decreasing trends were observed: in South-west part of the basin at Debre Tabor & Gonder Airport station with the MK statistic (Z = -0.249& -0.682) respectively and in Eastern part of the basin at Axum and Hawzen stations (Z = -0.375 & -0.577) respectively.

Change point results: Pettitt test is used to identify a change point in a time series (Equation 6), and assumes that the observations form an ordered sequence [12]. Results from Pettitt tests shows that reveal statistically significant shifts for monthly rainfall at the significance level of 0.05. It is clear from (Table 3 and Fig 3) that all four rainfall stations at Axum, Debretabor, Gonder Airport and Hawzen faced a shift downward of monthly rainfall in the years 2008, 1998, 2008 and 2002, respectively, with significant abrupt changes for significance level alpha equal to 0.05. An opposite observation is observed in other rainfall stations, which reveals a shift upward of monthly rainfall.

Table 3 Mann-Kendal and Pettit non-parametric trend test results for rainfall indices

			Mann Kendall Test			Pettit Test		
S.No	Station Name	Data Period	Z	Critical Value	Trend	Change point	P	Shift
1	Axum	1992-2012	-0.375	(-1.96, 1.96)	Decreasing	2008	0.961	Downward
2	Debre Tabor	1988-2013	-0.249	(-1.96, 1.96)	Decreasing	1998	0.726	Downward
3	Gonder AP	1953-2004	-0.682	(-1.96, 1.96)	Decreasing	2008	0.88	Downward
4	Hager Selam	1994-2012	0.249	(-1.96, 1.96)	Increasing	1995	0.708	Upward
5	Hawzen	1971-2012	-0.577	(-1.96, 1.96)	Decreasing	2002	0.773	Downward
6	Korem	1985-2012	1.031	(-1.96, 1.96)	Increasing	1991	0.395	Upward
7	Lalibela	1976-2004	1.516	(-1.96, 1.96)	Increasing	1983	0.165	Upward
8	Maichew	1971-2012	1.105	(-1.96, 1.96)	Increasing	1976	0.109	Upward
9	Mekele AP	1980-2012	0.551	(-1.96, 1.96)	Increasing	1990	0.69	Upward
10	N/Mewucha	1986-2004	0.068	(-1.96, 1.96)	Increasing	1988	0.949	Upward
11	Wukro	1992-2012	0.554	(-1.96, 1.96)	Increasing	2003	0.541	Upward

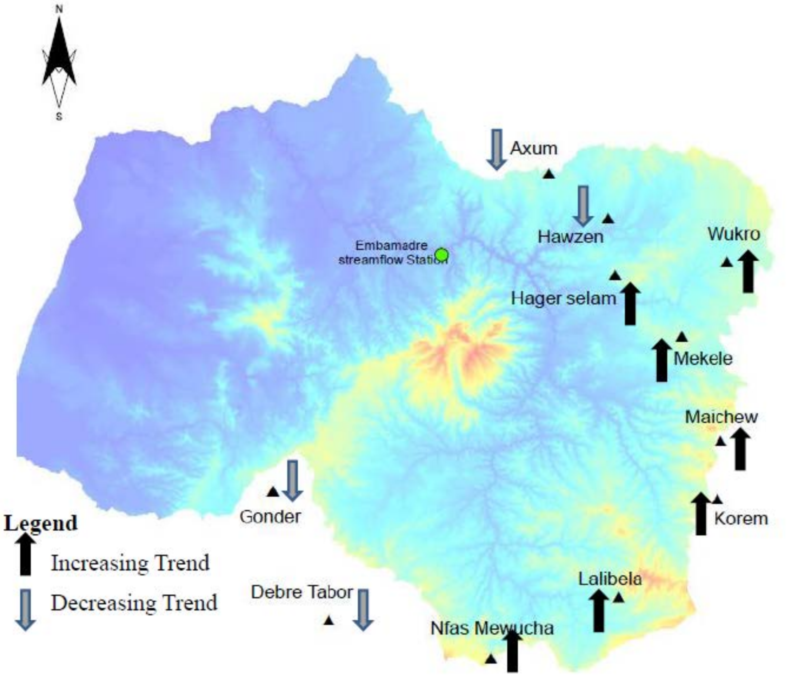


Fig 3 Trend test results of rainfall in Tekeze river basin

3.2 Streamflow Variability

The variability is described by IHA analysis using non-parametric statistics (median and coefficient of dispersion), because the hydrological time series are not normally distributed, but are positively skewed. The flow patterns are consistent with the summer and Belg rainfall regime, with the highest flow and rainfall events in June–September. Table (4) presents a spatial stream flow trends for selected hydrological indicators for the periods 1994–2008 with the slope of the trend lines and P values for the gauges located at the outlet, or the most downstream point of Tekeze River Basin at Embamadre. There is a significant trend of decreasing mean flow in June as this month is the start of the rainy season (Kiremt), when the Tekeze dam levels are lowest and water requirements highest for Hydropower. This trend is consistent with the increasing trends of minimum flows, as exemplified by the 7-day minimum. It can be also seen that the count of low pulses increased significantly, which indicates the more frequent occurrence of low flows.

Another striking trend is the significant increase in the number of reversals. Reversals are calculated by dividing the hydrologic record into “rising” and “falling” periods, which correspond to periods in which daily changes in flows are either positive or negative, respectively. The number of reversals is the number of times that the flow switches from one type of period to another. The observed increased number of reversals is likely due to the effect of flow regulation and water abstractions.

Altered variables at this site frequently included variables from all five IHA groups (Table 2). At Embamadre with significant hydrologic alterations in IHA Group 1 had decreased flows for summer season (July – October) and increases for other months. In IHA Group 2 magnitude and duration of annual extremes the minimum flow durations are increased and the maximum flow duration decreased. Relatively little number of significant hydrologic alterations were detected in IHA Group 3 variables (Timing of extremes). The variables in IHA Group 4 that were significantly altered in low pulse count and duration, alteration in high pulse and duration were found to be fewer. IHA group 5 variables quantify the rate and the frequency of changes rise rate, fall rate and reversals were significantly altered especially the fall rate.

Out of the 33 IHA indicators, Embamadre gauge had 27 significant trends, 6 of them negative, indicating a major shift in flow regime. The increasing trends occur in all months, but are more pronounced during low flow months, particularly Febreuary to June (Table 4) also a decreasing trend in the month of August. There is a significant decrease in high flows and small floods and an increase in extreme low flows. Tekeze River Basin is where most positive trends occur, particularly significant during the months of Febreuary, March and June but a decreasing trend in August. This research shows an increased duration of 1-, 3-, 7-, 30-, and 90-days minimum flow, an increased fall rate and base flow and decreased duration of 1-, 3-, 7-, 30-, and 90-days maximum flow, and decreased rise rate.

These analysis results evident that, parts of the hydrologic parameters of the Tekeze River watershed have been severely altered during the past century. We suggest that the majority of these alterations are due to anthropogenic impacts including Reservoir and agriculture, and to lesser degree of urbanization and other sources. One of universal results of these analyses was that larger streams have an increased number of hydrologic alterations. Larger watersheds are more likely include multiple land use types, and more likely to have upstream reservoirs.

Table 4 Results of IHA analysis for Tekeze basin at Embamadre

IHA group	Unit	Median	CD**	Slope	p-value
Monthly magnitude					
October	m3 s-1	138.20	0.99	10.35	0.001
November	m3 s-1	67.45	1.01	11.44	0.001
December	m3 s-1	36.40	2.48	11.28	0.001
January	m3 s-1	32.85	3.56	13.39	0.001
February	m3 s-1	25.08	7.10	16.80	0.001
March	m3 s-1	22.80	7.88	16.39	0.001
April	m3 s-1	30.30	5.00	15.29	0.001
May	m3 s-1	28.55	4.23	17.64	0.005
June	m3 s-1	73.65	2.38	16.02	0.010
July	m3 s-1	483.10	0.74	6.65	0.500
August	m3 s-1	920.80	0.84	-10.07	0.500
September	m3 s-1	357.00	0.55	2.92	0.500
Magnitude and duration of annual extreme					
1-day minimum	m3 s-1	8.40	2.10	4.95	0.005
3-day minimum	m3 s-1	10.02	5.68	8.36	0.001
7-day minimum	m3 s-1	14.61	4.50	9.30	0.001
30-day minimum	m3 s-1	17.72	5.10	11.15	0.001
90-day minimum	m3 s-1	24.81	4.12	12.22	0.001
1-day maximum	m3 s-1	2436.00	0.64	-33.14	0.500
3-day maximum	m3 s-1	1933.00	0.59	-28.57	0.250
7-day maximum	m3 s-1	1540.00	0.57	-26.67	0.250
30-day maximum	m3 s-1	1152.00	0.73	-17.37	0.500
90-day maximum	m3 s-1	736.40	0.80	-3.33	0.500
Timing of annual extreme					
Date of minimum	Julian date	147.50	0.18	6.18	0.100
Date of maximum	Julian date	231.50	0.05	0.87	0.100
Frequency (days) and duration of high and low pulses (per year)					
Low pulse count	No	4.50	1.67	-0.40	0.001
Low pulse duration	Days	7.00	1.43	-0.29	0.500
High pulse count	No	5.00	0.65	0.72	0.025
High pulse duration	Days	3.00	2.00	0.04	0.500
Rate and frequency of water condition change					
Rise rate	m3 s-1	33.48	0.94	-0.21	0.500
Fall rate	m3 s-1	-4.50	-2.44	-0.75	0.005
Number of reversals	No	98.00	0.49	1.07	0.500

**CD is the coefficient of dispersion; October is end of rainy season of the water year

Altered variables at this site frequently included variables from all five IHA groups

3.3 Impact of the Tekeze Arch Dam on Stream flows

Tekeze Arch Dam is the main reservoir in the Tekeze River used to improve the assurance of Hydropower purposes in the Ethiopia. The two-period (1994–2008 and 2009–2014) analysis illustrates the main impacts of the Tekeze Arch Dam on the river flow regime, namely the dampening of peak flows and an increase in low flows. As shown in (Fig 4) the 7-, 30-, 90-days and monthly minimum flow increases after the Tekeze hydropower reservoir starts to operate in 2008. Similar impacts were found in studies in different parts of the world [18]. It can be seen that this reservoir is managed to augment the low flows and attenuate floods. This change in the flow regime influences the streamflow along the main stem of the Tekeze-Atbara River, tributary of Nile River.

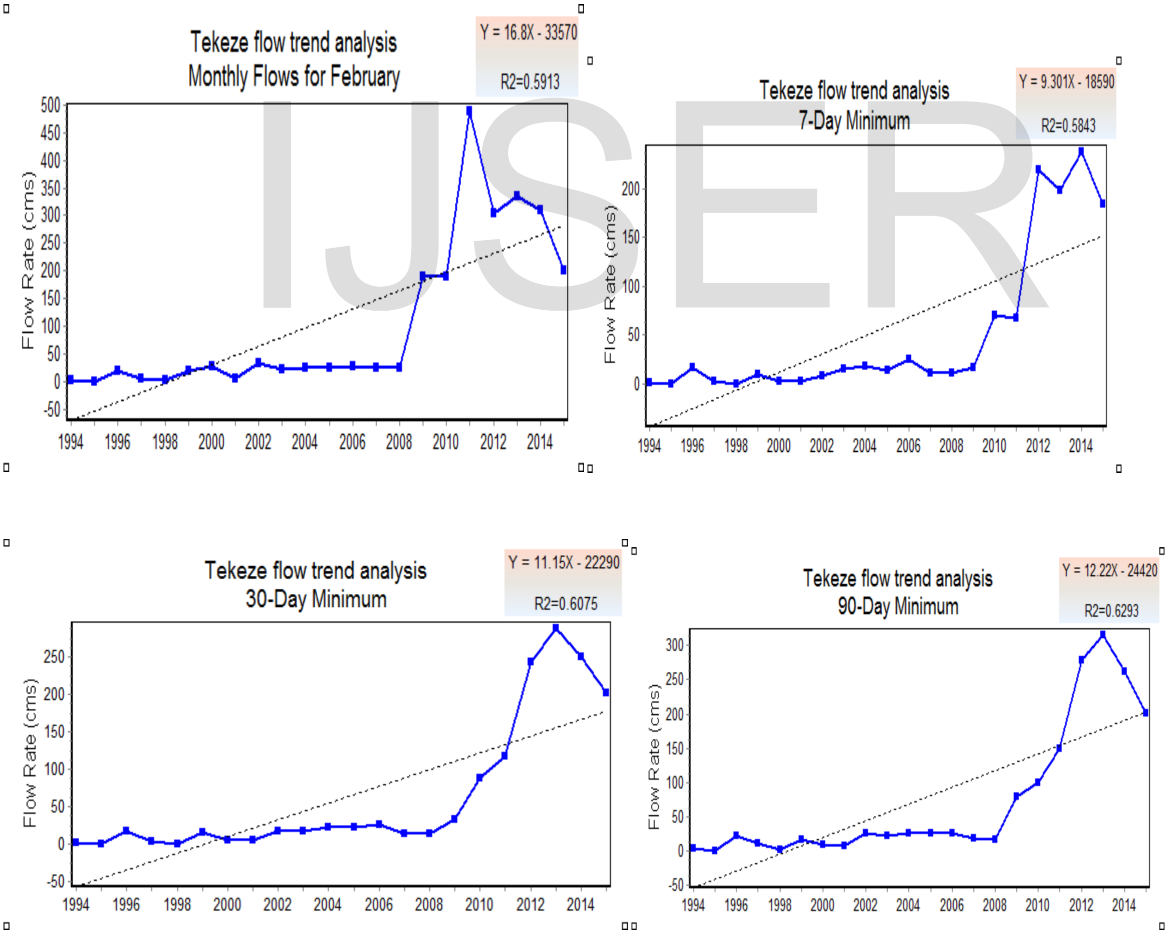


Fig 4 Trends of annual minimum flows at Embamadre Station

On the Tekeze basin, the strategic water uses, which have first priority for Hydropower Production, have a high impact on stream flows i.e high flow during rainy season decreases in the down stream due to impoundment and low flow during dry season increases due to flow released for power production. The daily flow data thereby obtained for the natural regime at Embamadre after 1994 represented in the chronological diagram of (Fig. 5) clearly show that as a consequence of the dam construction the magnitude of the daily regime was severely diminished, which is also in accordance to the expected.

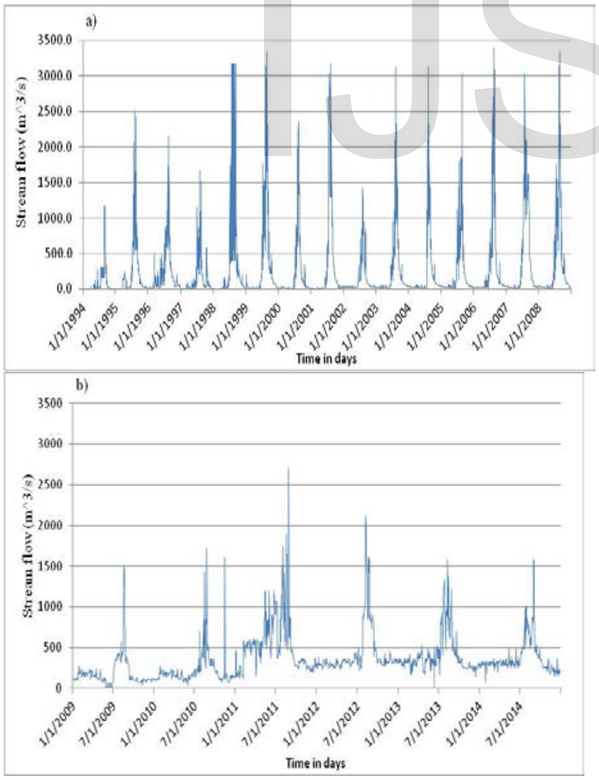


Fig 5 Daily flow at Embamadre station a) Before and b) After Tekeze hydropower reservoir operation

4. Conclusions and Recommendations

This research indicates that the investigation of trends in the hydro-climatic variables revealed a number of significant trends, both increasing and decreasing. Significant increasing rainfall trends were detected in most of the stations found in Eastern part of the Tekeze River Basin however, for some stations significant decreasing trends in Southwest and Northern part of the basin were detected. Statistical analysis performed using IHA at Embamadre stream flow station shows an increased in minimum flow duration, fall rate and base flow and also decreased in maximum flow duration and rise rate. After the inauguration of Tekeze Dam the hydrology altered i.e significant decline of high flows and increase of low flows, which were mainly attributed to store water in rainy season and releasing it during dry season.

The findings of this research can provide some information to the government and community of Ethiopia on the variability of rainfall and stream flow for future planned hydropower dams and irrigation projects in this basin. Nevertheless, further studies should be conducted to consider more characteristics of rainfall variability due to influence of regional features such as topography, water bodies, or transition in land cover and/or use as well as other climate variables that affect the stream flow of the basin. Also more studies and investments should be made on data collection and better use of available (scarce) data sets. The abandoning hydro-climatic monitoring network across the Tekeze River system should be overhauled. Recently, more climatic stations have been installed in small cities, but the coverage generally remains poor for the Semien mountainous areas, undermining proper hydro-climatological investigations.

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