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RESEARCH

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Quantitative analysis and modeling of minimum flow patterns in Temsa River, Abbay Basin, Ethiopia

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Abstract

The extent and occurrence of extremely low-flow events are necessary to determine the minimum river flow. Since the true probability distribution is usually not known, the best fitting distribution function describing the low flow in the catchment is important for reliable estimation of low flow and its frequency. The Temsa River is one of the most important tributaries of the Abay River Basin in Ethiopia and has a high ecological value for the country that can be affected by land cover changes. Climate influences watershed development, while landscape features control the accumulation and release of water over time, influencing stream flow, such as low flow. Therefore, analyzing the state of river discharge is important for the economic management of water resources. Rapid population growth has raised serious concerns about the adequacy of the Temsa River's future water intake in terms of quantity and quality. However, future water resources planning requires information on water flow variability and trends. The aim of this study is to identify and analyze the existing Temsa watersheds and their current status based on river water data collected by the Ethiopian Ministry of Water and Energy from 1997 to 2021 GC. Analysis focused on daily flow, mean annual flow, mean monthly flow, and consecutive 7-day mean minimum flow were included in the model. Methods for trend detection and quantification were the Mann–Kendall test (MK) and Sen's slope estimator (SS). The results of the MK and SS tests indicate the existence of a trend of statistical significance. The study shows a positive trend for two models and a negative trend for the other two models. The daily discharge analysis and the annual average flow analysis show a decreasing trend and the second model shows an increasing trend. BFI results show that the proportion of groundwater in the watershed is moderate, 73.6%, and the lognormal distribution fits the frequency analysis data.

Keywords: Kendall's test, Trend, Low flow, Sen's slope, Base flow

Introduction

The availability of water resources for agriculture, industry, and cities is the basis for the well-being and sustainable development of modern human societies. Among these resources, rivers provide many benefits to humankind, such as hydroelectric power generation, waterways, recreation, and fisheries. Rivers provide important ecosystem services such as water purification and climate regulation, in addition to their important role in maintaining biota and biodiversity. Sustainable water resource management therefore requires a proper understanding of the behavior of watershed hydrological systems and processes that ultimately affect water flow variability [1]. The effects of climate change are becoming more and more obvious and are becoming a threat to the environmental system. This climate change can significantly affect extreme weather changes, such as prolonged drought or extreme flooding. Reliable low-water estimates of the river regime are essential for water resource planning and management [20]. Low-water levels are an integral seasonal component of the hydrological regime whose quantification is critical for efficient development and integrated management of water resources as well as maintaining the quantity and quality of water used for irrigation, recreation and wildlife conservation. In general, it is considered that the actual flow occurs in the river in time during the dry season of the year. Low flows can be summarized by a number of measures or indicators. Among them, base flow index is one. "BFI" is defined as the rate of base flow to the total volume flow of the river and many studies have shown that it is related to a number of climatic and watershed factors [7, 21].

The MK test evaluates whether a trend is increasing or decreasing over time, rejecting the null hypothesis (stationarity) and accepting the alternative hypothesis. A simple definition of Sen's slope is the median of all pairwise slope values in a set of observations. These authors found that regulation and diversion projects had a significant impact on increasing minimum flows and decreasing maximum flows, but raised questions about ecosystem modification. Currently, there are no studies that have been conducted on the Temsa River specifically on low flow analysis; rather, a review based on land use land cover change on the Temsa River indicates a change of LULC and general study on the Nile basin. Therefore, the purpose of this paper is to focus on identifying and analyzing water flow trends in the Temsa catchment based on station discharge records for the main Temsa over the period 1997–2021 GC. This type of research is important because with proper knowledge of available water flows and associated water levels, inland waterways and their structures can be properly and safely planned [4, 11, 14]. With the increasing focus on surface water management, information on river characteristics and trends is routinely required to maintain water quality standards. Low-flow information can be quantified in a number of ways, depending on the types of data available and the desired output information. River discharge is an important topic in water resource research, and many studies have been conducted over the past 20 years, including analysis of low-flow frequency, base-flow separation, estimation of low-flow in ungauged basins, and research on low-water ecology in rivers studied for a long time over the world [8].

Water flows vary from year to year in Ethiopia and around the world [5, 15, 18, 19, 25]. In case of such variability, water resource management decisions can only be made based on river stream flow analysis. Therefore, water flux intensity (low or flood) analysis is important for water resource planning and development [17]. The ability to assess water flow at any point along a river is critical to effective integrated river management today [12, 13, 23]. Stream flow characterization is necessary for the implementation of water resource projects such as dam construction, aquatic ecosystem conservation, water abstraction licensing, runoff management, commercial vessels, and recreational area management [2, 3, 9]. The paper provides information about the characteristics of the Temsa River, particularly in relation to low flow and its trend. It enables the reader to understand and manage water resources effectively. The paper explores important research questions, including the role of groundwater from the Temsa River, the patterns of stream flow in Temsa, and whether the river is perennial. Answering these questions is vital for optimizing water resource allocation and planning projects related to water resources.

Methods

Weather condition of Temsa River

The Temsa River is located in the southwestern part of the Oromia Region in Ethiopia and it flows into the Lower Dedessa sub-Basin. This basin is partly situated in the Southern Countries and Ethnic Regions of Ethiopia. The Abay River Basin, the largest river basin in Ethiopia, can be found at coordinates 8° 4′ 54.84″ N and 36° 44′ 35.52″ E. The elevation of the Basin ranges from 1274 to 3145 m above mean sea level. Within the Temsa catchment, the elevation ranges from 1720 to 2088 m above sea level. The region mostly experiences a humid tropical climate with heavy rainfall, especially during the wet season known as Kiramt. The distribution of precipitation in the Temsa basin varies from highlands to lowlands. The months with the highest rainfall in the study area are June, July, August, and September, while March, April, and May are the driest months. The mean annual precipitation (1997 to 2021 GC) in the study area varies from about 634 mm in Bedele to 16,610 mm in Jimma, with mean annual temperatures between 16.38 and 37.55 °C. Average temperatures of the study area vary between 11.60 and 37.55 °C [6]. Detail of the location map of the study area is shown in Fig. 1.

Software

ArcGIS, BFI+, and Xlstat software were chosen to conduct this study because they can meet the goals set. ArcGIS was used to delineate study area map that shows the exact location of the longitude and latitude of stations, whereas BFI^{+} and Xlstat provide a base flow index of the site under study and analysis and interpretation of trends of the station under study respectively.

Base flow index software

To know the surface over flow contribution of the rivers in the basin, the baseline runoff must be separated from the gauge stream flow data (total hydrograph). Estimating subsurface contributions to rivers allows watershed planners to assess water availability, water use allocation, river assimilation capacity, and aquatic habitat needs. A baseline runoff index was used to calculate the contribution of groundwater to stream flow runoff. Divide the total amount of base flow by the total amount of flow for the specified

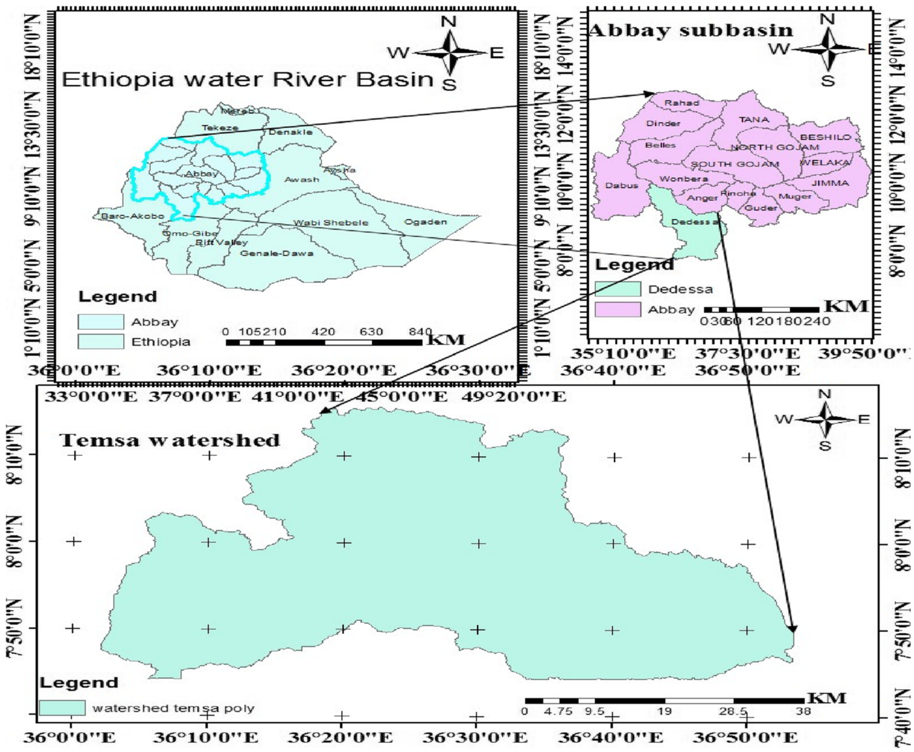

Fig. 1 Map of the Temsa catchment

time period to get the base flow index. This index is important in describing the geology of the site and aquifer profile of the river bank [10]. Base flow was determined from the hydrograph using the BFI^{+} software program. Large value of base flows index indicates dominant groundwater contribution and small value of BFI indicates flashness or runoff property. This value of BFI was between zero and one.

ArcGIS software

ArcGIS is a family of client, server, and online geographic information system (GIS) software developed and maintained by Esri. ArcGIS was first released in 1999 and originally was released as ARC/INFO, a command line-based GIS system for manipulating data. ARC/INFO was later merged into ArcGIS Desktop, which was eventually superseded by ArcGIS Pro in 2015 [22]. ArcGIS is a powerful geographic information system (GIS) software that can be used for trend analysis in various fields. Some of the common uses of ArcGIS in trend analysis include:

Environmental analysis: ArcGIS can be used to analyze trends in environmental data such as temperature, precipitation, air quality, and land cover changes. This can help in understanding climate change patterns, identifying areas of environmental degradation, and developing strategies for sustainable resource management. Overall, ArcGIS provides a comprehensive set of tools for spatial analysis and visualization, enabling users to identify and understand trends in various datasets. This information can then be used to make informed decisions and develop effective strategies in different fields.

Overall, the strengths of ARCGIS lie in its comprehensive spatial analysis capabilities, advanced mapping and visualization tools, integration with different data sources and formats, geospatial data management capabilities, collaboration features, and extensive documentation and support https://enterprise.arcgis.com/en/portal/latest/administer/windows/choosing-between-an-arcgis-online.

XLstat software

XLSTAT is a software package that is widely used for statistical analysis and data mining in Excel. While it is not specifically designed for trend analysis, it can still be used for this purpose by applying various statistical techniques and tools available in the software. Some of the uses of XLSTAT in trend analysis include the following: Time series analysis: XLSTAT provides several tools and models for analyzing time series data, such as autoregressive integrated moving average (ARIMA) models, exponential smoothing, and seasonal decomposition. Regression analysis: XLSTAT offers a wide range of regression models, including linear regression, polynomial regression, logistic regression, and multiple regressions. These models can help identify trends and relationships between variables. Forecasting: XLSTAT includes forecasting capabilities that allow users to predict future trends based on historical data. This can be useful for businesses and organizations to anticipate future demand or market trends. Data visualization: XLSTAT provides various graphical tools for visualizing data, including scatter plots, line charts, and time series plots. These visualizations can help identify trends and patterns in the data. Overall, while XLSTAT may not have specific features dedicated solely to trend analysis, its wide range of statistical tools and models make it a versatile software that can be used effectively for trend analysis in various fields https://www.beijerelectronics.com/en/Products/frequency-inverters/software.

Overall, the strengths of XLSTAT lie in its integration with Excel, a wide range of statistical techniques, user-friendly interface, extensive documentation and support, continuous development, and compatibility with different versions of Excel.

Selection of probability distribution and tests of performance evaluation

The selection of probability distribution function (PDF) is one statistical information used to model any time series hydrological data, such as rainfall, temperature, and stream flow to compute the magnitude and frequency of time series data. The best-fitting model was indicated by the distribution closest to the line, and the ability of the distribution to fit the model was assessed by comparing simulated and actual observed values of hydrological data under study, and also it can be provided by using XLstat software. The performance of this distribution is tested by different methods and software in conjunction with RMSE value computed by Eq. (1).

RMSE: a technique of calculating the error of the identified distribution based on simulated and observed stream flow data, and the best-fit distribution is selected on behalf of its minimum error of computed RMSE [9, 16, 24]:

$$\text{RMSE} = \sum \left[(q_\text{o} - q_\text{m})^2 / \text{n} \right]^{0.5} \tag{1}$$

where

q_o: observed discharged

q_m: predicted discharge

The magnitude and frequency can be calculated using the chosen distribution after scale, location, and shape parameters have been computed by selected parameter computation techniques like linear moment methods, maximum likelihood methods, and so on. Some formulas for computation of magnitude and return period of flow are given in Eqs. (2,3,4 and 5).

For the GEV distribution

$$Q_t = \widehat{Z} + (1 - (-\ln(1 - 1/t)^K) \text{ for } K \neq 0 \tag{2}$$

$$Q_t = \widehat{Z} + (\ln(-\ln(1 - 1/t)^K) \text{ for } K = 0 \tag{3}$$

For GPA distribution

$$Q_t = \widehat{Z} + (\ln(1/t)^K) \text{ for } K = 0 \tag{4}$$

$$Q_t = \widehat{Z} + (1 - (1/t)^K) \text{ for } K \neq 0 \tag{5}$$

where σ = scale parameter

Q_t: discharge

t: time of occurrence

$\hat{Z}$: mean

K: shape parameter

Mann–Kendall's trends analysis of stream flow

The Mann and Kendall trend (MK) was used to assess whether a low flow trend was present at selected stations or not. A common nonparametric technique for examining trends in hydrological time series data is the MK trend test. Based on the significance of the test results, the presence of a trend was classified as either no trend, an increasing trend, or a decreasing trend. A positive Mann–Kendall value indicates an upward (increasing) trend, a (negative) value indicates a downward (decreasing) trend, and 0 indicates no trend [5]. MK and SS tests are nonparametric statistical methods for evaluating trends. These indices are the two most robust methods for detecting and estimating trend magnitude and are therefore often used to assess temporal variability in hydrometeorological variables. These two indices are easily computed by XLstat software and empirically computed by Eq. (6).

$$tau = \sum_{I=1}^{N-1} * \sum_{J=1+1}^{N} \sin(Xj - Xi) \tag{6}$$

where Xj and Xi are the daily values in days j and i, $j > i$, respectively

$\sin(Xj - Xi)$=1, 0, and − 1: for $Xj - Xi$ >1, $Xj - Xi$ =0 and $Xj - Xi$<0 respectively.

Table 1 Trends of Temsa River

Model tests	Daily flow	7MAM	Average monthly	Average annually
Kendall's tau	− 0.059	0.255	0.02	− 0.140
SS	− 50.003	70	982.000	− 42.000
P	0.01	0.087	0.594	0.338

Therefore, Temsa River would be influenced by a factor like land use land cover change and it requires a management strategy to increase stream flow

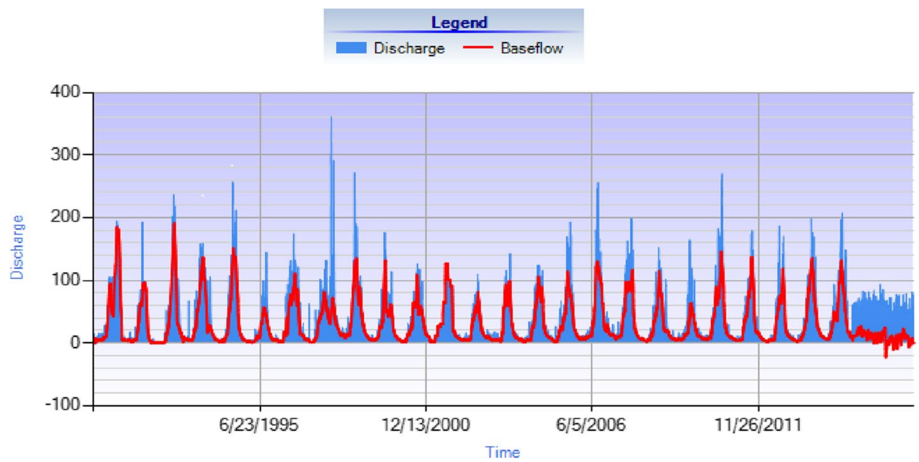

Fig. 2 Base flow and hydrograph of the Temsa River

If $n < 10$, the value of |tau| is compared directly to the theoretical distribution of S derived by Mann and Kendall.

Sen's slope trends analysis of stream flow

The Sen's slope estimator, commonly symbolized as SS, is a nonparametric measure that can estimate the magnitude of a trend change. This detection slope value is provided using the XLstat software and indicates an increasing or decreasing trend when the value is positive or negative.

Results and discussion

Stream flow trends

The methodology used in this study is described through a series of steps aimed at identifying existing trends that depend on stream flow data of Temsa River. In this study, the presence or absence of trends in annual average, 7-day MAM flow (consecutive 7-day mean average minimum flow), daily average discharge, and monthly average discharge were evaluated by using 25 years of available Temsa River flow data from 1997 to 2021 GC. Flow trends were assessed independently using the Mann–Kendall test (MK) and Sen's slope. Long-term low-flow quintiles were calculated using low-flow frequency analysis. The results show that there is a statistically significant decreasing trend for the daily average flow analysis and the average annual flow as the value of both tau and SS were negative, and a nearly positive trend for the other two cases, as shown in Table 1.

Table 2 Xlstat results for distribution selection and its effectiveness

Distribution	Probability fit
Weibull	0.789
Gamma	0.970
GEV	0.982
Normal	0.538
Log-normal	**0.9990**

Performance evaluation of the selected distribution was done by computing the RMSE of parameter obtained by software using Eq. (6) to be 0.013

Table 3 Magnitude of low flow of Temsa River by XLstat

Return period	Discharge
5	1.417
10	1.719
25	2.558
50	3.373
75	4.842

As observed from the result decreasing trend dominated which requires attention toward sustainable management.

Base flow calculation by BFI$^+$

According to science, the contribution of groundwater recharge increases with the number of base flow indices. On the other hand, the groundwater contribution decreases as the number of BFIs decreases. The calculated BFI based on the BFI + software results was 0.736. Therefore, according to the BFI + software, the BFI for this station is 73.6%, which has a moderate impact on storage. From Fig. 2, it can be observed that stream flow of the study area seems to direct runoff as a great variation observed among maximum and minimum flow. Flows therefore indicate that the water is likely surface runoff and not groundwater recharge. Therefore, the development of hydropower facilities such as dams and reservoirs and the implementation of continuous afforestation strategies in this watershed are necessary to increase the contribution of groundwater to stream flow and prevent future droughts.

Identification of distribution and evaluation of accuracy of the selected distribution

Based on the discharge statistics of the Temsa River, it is possible to determine the probability distribution function used to calculate the stream flow quintiles having different return periods. Among different distributions applied, the most appropriate distribution for calculating the future water flow rate of the Temsa catchment is the log-normal distribution as shown in Table 2, because of its highest probability of fitting the data. Depending on the chosen probability distribution, flow rates of different return periods were determined: such as flows 1.417, 1.719, 2.558, 3.373, and 4.842 m^3/s with return periods of 5, 10.25, 50, and 75. The result is that as the number of return period increases, the magnitude of the flow increases, but the probability of exhibiting a minimum flow decreases [10]. As observed in Table 2, the distribution ranked as a first order was lognormal and GEV. This validates that the flow frequencies of the Temsa stations were accurately determined using both methods.

Parameter and quintile estimation

The probability distribution function is computed by XLstat and the current flows for various quintiles are estimated as shown in Table 3. To obtain these results, the function of fitting the flow data and the ranking and descriptive statistics of the goodness-of-fit test were used. According to Table 3, flow quintile projections were made for return periods of 5, 10, 25, 50, and 75 years.

As observed from Table 3, stream flow having a 10-year recurrence interval should correctly show a minimum flow of Temsa River, although log-normal distribution best fits the data and is used to compute the magnitude of extreme events.

Conclusions

This study was conducted based on the stream flow of Temsa River collected from Ethiopian MoWE based on data from 1997 to 2021 GC that can be for 25 years. In this study, stream flow analysis was done based on daily flow model, average monthly flow model, annual flow model, and 7-day consecutive mean average minimum flow data. From this model, two model indicate an increasing trend and the other two model shows a decreasing trend. In other cases also, there should be a calculated value of base flow index that shows groundwater contribution to surface runoff. Depending on this fact, BFI calculated indicates 73.6% that shows moderate contribution of groundwater flow. A lognormal distribution was fitted to the data and goodness-of-fit tests were performed using RMSE. This study shows the decline patterns that the Temsa River can produce by the Mann–Kendall trend test and Sen's slope estimator when using daily flow and average annual water flows, and when using monthly averages and 7MAM values indicates an increasing trend. The results served as the basis for planning, drought risk management, and corresponding hydraulic engineering design in the study area. It is also proposed to apply this model to other sections of Ethiopian rivers to address the information problem of river flow.

Abbreviations

BFI	Base flow index
DEM	Digital elevation model
FFA	Flow frequency analysis
GC	Gregorian calendar
GEV	General extreme value
GIS	Geographical information system
Ln	Log-normal
MAM	Mean average minimum
MoWE	Ministry of water and Electricity
PDF	Probability distribution function
RMSE	Root mean square error
tau	Kendell's tau
SS	Sen's slope
XLstat	Excel statistics
7MAM	Consecutive 7-day mean average minimum flow

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Authors' contributions
All authors have read and approved the manuscript.

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Availability of data and materials
All data are included in the article, if needed it submitted upon request.

Declarations

Ethics approval and consent to participate
I hereby state that the paper titled "Quantitative Analysis and Modeling of Minimum Flow Patterns in Temsa River, Abay Basin, Ethiopia" is purely my original work, has never been published, and all data source citations declared are included.

Competing interests
The authors declare that they have no competing interests.

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