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Research Article

Flood Frequency Analysis Using Gumbel Distribution Method: A Case of Robigumero River, Abay Basin, Ethiopia

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Abstract

Hydraulic structures like weirs, dams, spillways, and bridges require precise estimation of flood peaks at the intended return period in order to be planned, built, and maintained. In this paper, the findings of a study conducted on the Robigumoro River and the flow measurements taken are presented. The flood frequency analysis of the Robigumoro River was performed using the Gumbel distribution, which is a probability distribution commonly used for modeling river flows. This analysis is crucial as it aims to safeguard the lives and properties located downstream from the catchment area. The Gumbel distribution was employed to model the highest annual river flow over a span of 20 years (1990-2009). The investigation was carried out by the Ethiopian water and energy office, Abay Basin Development Authority. The Robigumoro River's maximum annual discharge over a 20-year period (1990–2009) was modeled using Gumbel distribution technique. From the trend line equation, R^2 value of 0.935 which shows that Gumbel's distribution is suitable for predicting expected flow in the river. It can be concluded that the Gumbel distribution can accurately forecast expected river flow. The flood peak values were calculated using the same procedure for various return times. This helps with storm management in the research region. The estimated discharges obtained using the Gumbel's distribution and return periods (T) of 2 years, 10 years, 50 years, 100 years, 150 years, 200 years, 300 years and 400 years are 177.327m^3/s, 320.784m^3/s, 446.553m^3/s, 499.722m^3/s, 530.727m^3/s, 552.698m^3/s, 583.38m^3/s, and 605.577m^3/s respectively. The accuracy of flood forecasts in the basin indicates their potential use in various applications such as the design of crucial hydraulic structures, river reach planning, construction of bridges, and conservation efforts for Robigumoro watershed.

Keywords

Flood Frequency Analysis, Gumbel Distribution Method, Robigumoro River

1. Introduction

There has been an ongoing problem in hydrology regarding the calculation of design peak discharges on catchments with limited data. Accurate estimates of flood quantiles are crucial for the efficient design of hydraulic structures [1, 13]. However, the necessary historical data to determine flood statistics are often unavailable or may not accurately represent the catchment area due to changes in watershed characteristics like urbanization [3, 4]. In developing countries like Ethiopia, hydrological data may be scarce, brief, or completely non-existent, making it difficult to accurately assess the basin being studied [1, 13]. The Blue Nile River Basin is the primary origin of the Nile River, which holds the record for

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being the longest river in the world. This basin supports the livelihoods of millions of people in ten African countries, including Ethiopia, Burundi, the Democratic Republic of Congo, Rwanda, Tanzania, Kenya, Uganda, South Sudan, Sudan, and Egypt [2]. Due to climate change and population growth in these countries, it is necessary to adopt new approaches to ensure a continuous and secure water supply for drinking, hydropower, and agricultural purposes in the Nile River Basin [14]. As a result, the Ethiopian government has initiated various water resource projects in the Upper Blue Nile River Basin. This has inspired our investigation into a more reliable method for predicting flood frequencies in the region, which can help enhance the design reliability of water resource projects. It is common practice to use different quantiles from the developed flood frequency curve for dam safety analysis. For instance, in France, a flood with a return period of 100 years is recommended for flood hazard mappings, while a flood with a return period of 104 years is considered for the design and safety analysis of large-scale water infrastructures. Additionally, several countries have established frameworks suggesting which probability distribution should be used for flood frequency analysis, such as the lognormal distribution in China, the three-parameter log-Pearson type 3 distribution in the United States of America, and the generalized extreme value distribution in the United Kingdom [15-17]. However, despite the importance of investigating a robust flood frequency prediction model to improve design and efficiently plan and manage regional water resource projects, flood frequency analysis in the region has not received much attention. Therefore, this study aims to investigate a reliable method for flood frequency analysis to facilitate improved design, planning, and management of the water resources of the Blue Nile River. Many research studies have been conducted worldwide to determine the most appropriate probability distribution for analyzing flood frequency in different regions [2]. In a study by Singh et al. [18], the performance of various extreme value distributions was compared using data from 172 gauging stations in Ireland. It was found that the Gumbel distribution performed better than the Frechet and Weibull distributions. Similarly, Seckin et al. [20] analyzed flood frequency using data from 543 gauging stations in Turkey and concluded that the Gumbel distribution provided a better fit to the data compared to the generalized logistic and log-Pearson type-III distributions. An estimate of the frequency of a The most popular technique used by engineers and hydrologists worldwide is called Flood Frequency Analysis (FFA), which basically entails estimating peak flood flows within a range of probabilities that won't be exceeded. A probabilistic model is fitted to a sample of annual flood peaks for a particular regional catchment during an observation period using flood frequency analysis. Extreme events at long repetition intervals can be predicted with the aid of the established model parameters. For the purpose of managing flood plains, a trustworthy estimation of flood frequency is crucial. These include planning and placing hydroelectric structures, minimizing the costs to governments and private businesses associated with floods, evaluating the risks associated with flood plain development, and safeguarding the public [10, 11]. Research has employed various statistical distributions to measure the likelihood and severity of floods; however, none of these distributions are universally recognized or nation-specific [3]. Every year, a significant amount of capital is allocated towards the mitigation and safeguarding against flood impacts. This is achieved through the implementation of either structural measures, such as river training, the construction of storage dams, weirs, reservoirs, drainages, and culverts, or non-structural measures, including flood forecasting, catchment enrichment, channel development, and rescue operations. However, it is important to note that meteorological data can only provide limited and short-term forecasts with a high level of accuracy. These forecasts, although brief, can still offer an opportunity to mitigate the effects of flood events. Nevertheless, the unreliability of meteorological forecasts has resulted in numerous false alarms, causing people to no longer take these predictions seriously [19]. As a consequence of the inaccuracies in flood forecasting using rainfall data, statistical methods such as Normal, Extreme Value Type I, Log Normal, Log Pearson Type III, and others have been employed to predict floods. The primary objective of this paper is to conduct an analysis of flood frequency within the river catchment. This will be achieved by utilizing data on annual peak flow or maximum discharge, which has been obtained from the river spanning the years 1990 to 2009. The specific aims of this study are, firstly, to employ the Gumbel distributions in order to examine the annual peak discharge data pertaining to the Robigumoro River during the period from 1990 to 2009. Secondly, to make projections regarding flood design for various return periods, including 2 years, 10 years, 50 years, 100 years, 150 years, 200 years, 300 years and 400 years. The analytical findings derived from this study offer comprehensive insights into the expected discharge levels in rivers based on observations at various return periods. This data is exceptionally valuable for engineering applications, such as the development of infrastructure in close proximity to waterways that could potentially be influenced by inundation, or the creation of flood control systems to safeguard against projected occurrences [4]. These applications might encompass the planning and construction of reservoirs, bridges, and flood management systems that alleviate the risks posed by floods within the basin, while simultaneously offering crucial assistance in the management of local precipitation runoff [5]. The outcomes of the analysis produced from the investigation provide comprehensive data regarding the anticipated flow discharge in the river at different return periods, based on the observed data. This information will prove highly valuable for engineering purposes, such as the design of structures located in or close to the river that may be impacted by floods, as well as the development of flood structures to safeguard against anticipated events. This may encompass the construction of dams, bridges, and flood control facilities, all of which will contribute to the mitigation of flood disasters within the catchment area and greatly aid in the management of storm water in the surrounding region [8].

2. Description of the Study Area

The Jemma River is one of the biggest tributaries of the Blue Nile (Abay River) Basin and founds in the central highlands of Ethiopia, 180 km North of Addis Ababa. It includes parts of the Wollo, North Shewa Zones of the Amhara, and Oromia Regions. Jemma River is located in the East of the Blue Nile River Basin between 9° 05' 37'' – 11 °10' 07'' N latitude to 37° 12' 07''- 40° 0' 01'' E longitude and cover an area of 15720 km^2. From the number of small tributaries flowing from the east of the basin into the Jemma River, the Robigumero River is one of the major gauged tributaries. It covers the catchment area of 914.7 km^2 in between 9 °25' - 9 °55' N and 38 °54''– 39 °20' East position.

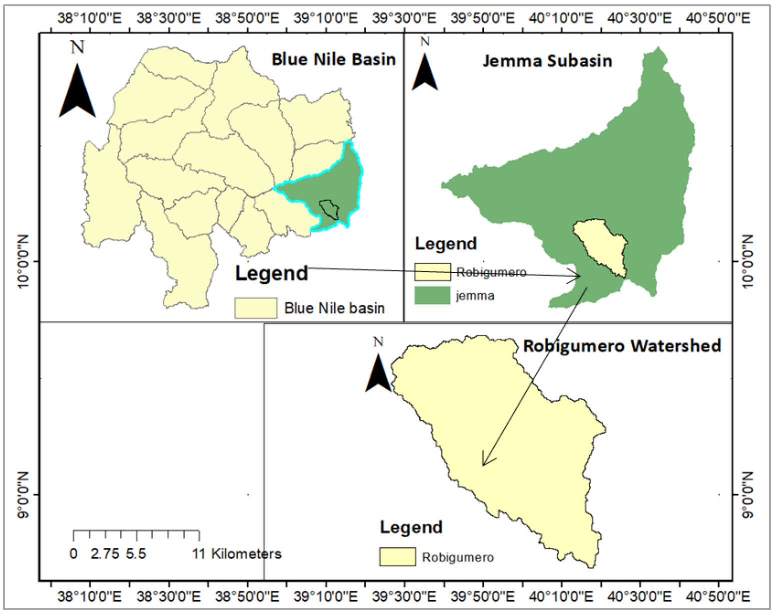

Figure 1. *Location of the Study Area.*

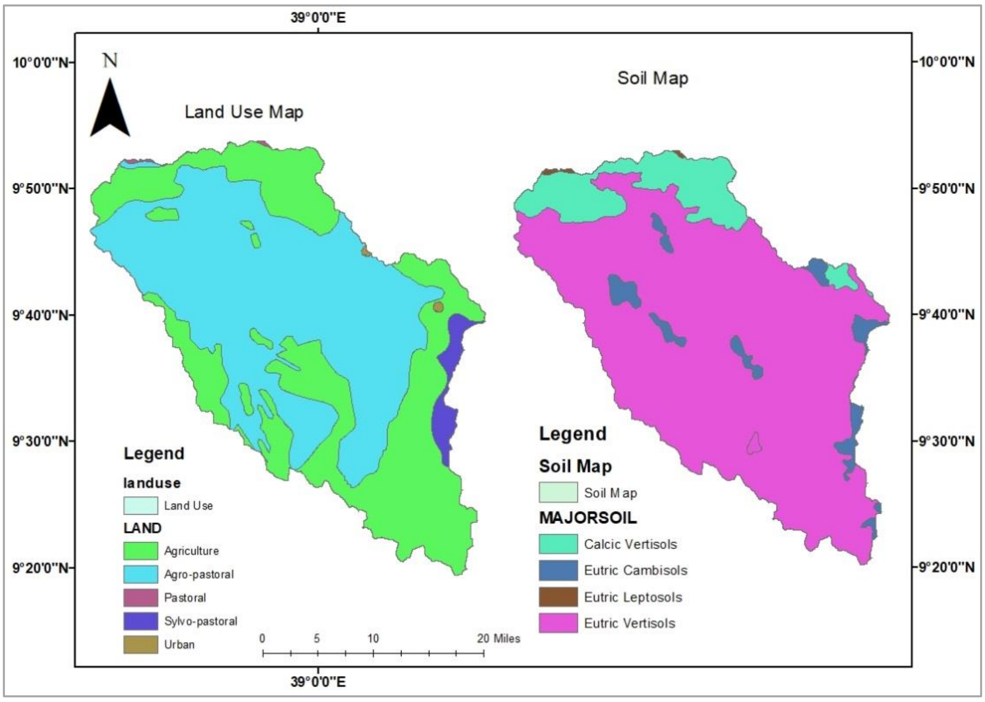

Figure 2. *Soil and Land Use Land Cover maps of Robigumero Watershed.*

Based on Figure 2, the main land cover in the study basin is predominantly agro-pastoral land, followed by agriculture, and sylvo-pastoral and urban area. However, there is a rapid conversion of the natural vegetation into agricultural crop land within the basin. This deforestation of woody vegetation and expansion of cultivated land is increasing in the study area. Consequently, these changes in land use can have an impact on the temporal and spatial dynamics of surface runoff. For instance, converting natural vegetation into agricultural crop land will result in an increase in surface runoff magnitude. As a result, this will affect the probability distribution identified in the region based on previous information. Therefore, it is crucial to regularly update the most appropriate flood frequency prediction model considering the changes in land use. Additionally, the topography of the study area reveals that the elevation ranges from 2500 to 3200 meters above sea level. The topographic map indicates that small-scale catchments exhibit a similar slope pattern, whereas medium- and large-scale basins display varied slope patterns. The required data for flood frequency analysis of Robigumoro River consists of the observed daily streamflow data. The hydrology department of the Ministry of Water, Irrigation, and Energy (MoWIE) recorded the streamflow in the Blue Nile basin, including the Robigumero watershed. However, the currently recorded streamflow data is no longer accessible. The Ministry of Water, Irrigation, and Electricity provided the available observed daily streamflow data collected at Robigumero gauging station from 1990 to 2009.

3. Methodology

The Gumbel distribution is a statistical technique often used to predict extreme hydrological events such as floods [12, 1, 9]. In this study it was applied to the analysis of flood frequency. This is because:

A. rivers are less regulated and therefore not significantly affected by reservoir manipulation, diversion or urbanization;
B. Flow data are homogenous and independent and do not show long-term trends.
C. The peak flow data cover a relatively long period (more than 10 years) and are of good quality.
D. no major tributaries whose inflow could affect the flood crest;

The equations for the method of Gumbel distribution and return period T are:

$$XT= Xm+KT^* \delta n\text{-}1 \quad (1)$$

$$KT= \text{frequency factor.} = \frac{YT-Yn}{sn} \quad (2)$$

Where: -

XT=annual maximum rain falls of T years return period (design storm).

Xm =mean of the annual maximum daily rain fall.

δn-1=standard deviation of annual rain falls.

YT =reduced mean obtained from the table for sample size.

Yn= reduced gamble extreme value distribution for sample size from table.

Sn =reduced standard deviation obtained from the table for sample size.

$$YT=-\ln^*\ln\left(1-\frac{1}{T}\right) \quad (3)$$

The maximum discharge data of Robigumoro Weir, from 1990-2009 (20 years flood data) were considered for the flood frequency analysis applying the Gumbel's distribution. The steps to estimate the design flood for any return period, given by Equation (2) is as follows:

Step I: Annual peak flood data was assembled from 1990 to 2009.

Step II: From the maximum flood data for n years, the mean Xm and standard deviation δn-1 are computed using:

$$\delta n\text{-}1=\sqrt{\frac{\sum(xi-xm)^{\wedge}2}{N-1}} \quad (4)$$

Step III: From the Gumbel's Extreme Value distribution Table, the value Yn and Sn are taken as 0.5362 and 1.0628.

Step VI: From the given return period Tr, the reduced variate YT is computed using Equation (3).

Step V: From Yn, Sn and YT, the flood frequency factor KT is computed using Equation (2).

Step VI: With use of Equation (1), the magnitude of flood is computed.

It is of great importance to confirm if the observed flood data collected in the catchment follows Gumbel distribution or not. In order to achieve this, the observed data is arranged in descending order (the highest coming first) and assigning the return period for each flood; the reduced variate corresponding to each flood is computed using Equation (3). A plot of the reduced variate and magnitude of flood is made on ordinary graph paper. If an eye fits to this plot suggest a straight line, then it is reasonable to conclude that the Gumbel distribution is a good fit for the observed flood data.

4. Result

The Gumbel distribution analysis was done following the above methodology and the results obtained are shown in Table 1. Also a plot of reduced variate v/s flood peak was plotted for Robigumoro River, which is shown in Figure 3. Table 1 presents the annual peak flow data for the Robigumoro River from 1990 to 2009. This data was collected through daily discharge measurements conducted by the Abay River Basin Development Authority. This paper demonstrates the outcomes and examination of Gumbel distribution. This was accomplished by employing Gumbel distribution Method.

Figure 3 illustrates the probability plot and flood frequency curve for Robigumoro River using Gumbel distribution. It is important to note that this paper solely presents the results and analysis of Robigumoro River as an example. Using the Gumbel's extreme value distribution analysis, our results agree with the study of O. Solomon and O. Prince [8] and N. Mujere [6].

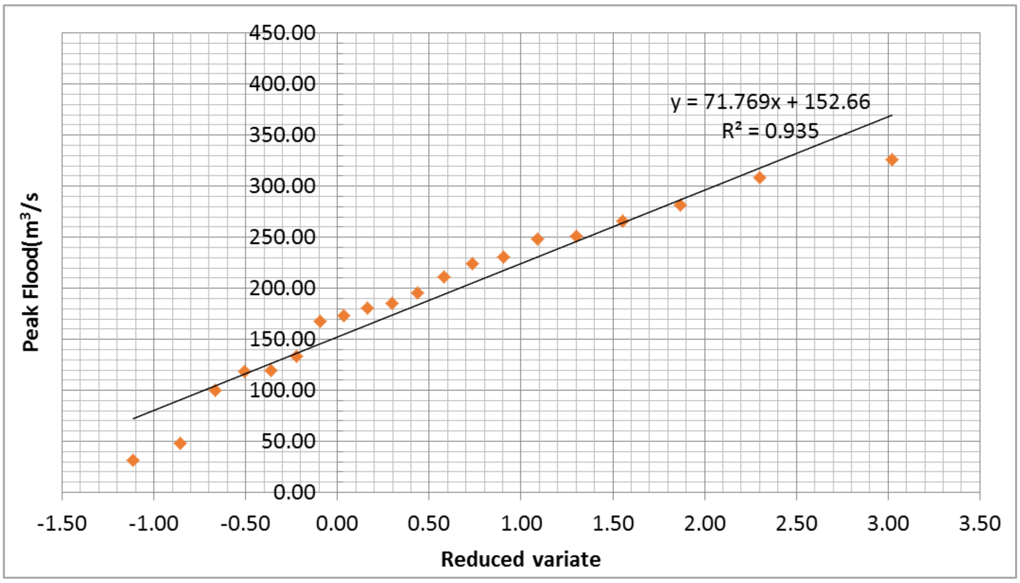

Figure 3*. Plot of Reduced Variate v/s Peak Flood for Robigumoro River.*

Table 1*. Gumbel distribution method Computation Table.*

year	Peak Flood (m^3/s)	Descending order=Xi	Order (m)	$Sx^2 = (x - \dot{X})^2$	Return Period $Tr = \frac{n+1}{m}$	Reduced Variate $Y = -ln.\ln\left(\frac{Tr}{Tr-1}\right)$
1990	308.18	326.36	1.00	18528.95	21.00	3.02
1991	173.45	308.18	2.00	13911.52	10.50	2.30
1992	167.70	281.92	3.00	8406.16	7.00	1.87
1993	180.78	265.63	4.00	5684.87	5.25	1.55
1994	265.63	251.55	5.00	3759.66	4.20	1.30
1995	133.88	248.09	6.00	3347.10	3.50	1.09
1996	248.09	231.13	7.00	1672.16	3.00	0.90
1997	231.13	224.51	8.00	1174.51	2.63	0.73
1998	224.51	211.54	9.00	454.08	2.33	0.58
1999	251.55	195.87	10.00	31.73	2.10	0.44
2000	195.87	185.24	11.00	24.91	1.91	0.30
2001	211.54	180.78	12.00	89.41	1.75	0.17
2002	118.96	173.45	13.00	281.57	1.62	0.04
2003	281.92	167.70	14.00	507.73	1.50	-0.09
2004	185.24	133.88	15.00	3175.54	1.40	-0.23
2005	119.35	119.35	16.00	5024.67	1.31	-0.36
2006	326.36	118.96	17.00	5079.40	1.24	-0.51

year	Peak Flood (m^3/s)	Descending order=Xi	Order (m)	$Sx^2 = (x - \dot{X})^2$	Return Period $Tr = \frac{n+1}{m}$	Reduced Variate $Y = -ln.\ln\left(\frac{Tr}{Tr-1}\right)$
2007	100.28	100.28	18.00	8091.70	1.17	-0.67
2008	31.60	48.66	19.00	20042.89	1.11	-0.86
2009	48.66	31.60	20.00	25164.71	1.05	-1.11
Mean, Ẋ		190.23				
Sum		3804.68		124453.27		
δn--1		80.93		7458.86		

N.B: δn--1. – Standard Deviation

Table 2. *Computation of Expected Flood along Robigumoro River.*

Return period	Reduced Variate $Y = -ln.\ln(\frac{Tr}{Tr-1})$	Frequency Factor $KT = \frac{Y-Yn}{sn}$	expected flood $XT = \dot{X} + KT * \delta n - 1$
2	0.367	-0.159	177.327
10	2.250	1.613	320.784
50	3.902	3.167	446.553
100	4.600	3.824	499.722
150	5.007	4.207	530.727
200	5.296	4.479	552.698
300	5.702	4.861	583.638
400	5.990	5.132	605.577

5. Discussion

The above results show that the maximum flow of 326.36 m^3/s was recorded in 2006 while the lowest flood flow of 31.60 m^3/s was recorded in 2008. The 20-year mean instantaneous flood flow is 190.23 m^3/s with a coefficient of variability 86%. Using the Gumbel distribution analysis, the floods with different recurrence intervals were also computed and the same are shown in Table 2. The results show the expected floods in the river reach for return periods of 2yrs, 10yrs, 50yrs, 100yrs, 150yrs, 200yrs 300yrs and 400yrs. From here, other values not shown in chart can be extrapolated or can be computed using the above mentioned method. The study's projected values are important in managing Robigumoro river extreme flood events. Same results are observed by N. Mujere [7] and O. Solomon and O. Prince [8].

6. Conclusion

From the flood frequency analysis carried out for Robigumoro River using 20 year's annual peak flow data. Figure 2 shows a plot of the reduced variate and peak flood of the river using the observed data. From the trend line equation, R^2 gives a value of 0.935. The value $R^2 = 0.935$ shows that the pattern of the scatter is narrow and that Gumbel distribution method is suitable for predicting expected flow in the river. Also the mean instantaneous flow in the river is 190.23 m^3/s which is having a return period of about 10 years as shown in Table 2 and it is visible in the flood peak data also. This means the prediction of floods in the basin is nearly accurate. This prediction of flood can be utilized in the designing of important hydraulic structures and bridges in the river reach. Also in case of extreme floods emergency evacuation of people can be carried out well in advance. Similar study can also be carried out on some other study region, as the method used for the study is having a constant formula, which remains spatially constant.

Abbreviations

FFA: Flood Frequency Analysis
MoWIE: Ministry of Water, Irrigation, and Energy

Conflict of Interest

The authors declare no conflicts of interest.

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