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Investigating the Available Water for Irrigation in the Tana Basin, Kenya

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ABSTRACT

The objective of this research paper was to establish water resources availability for agricultural production in Tana Basin. Frequency analysis techniques are used here to determine flood and low flow magnitudes required in the design of hydraulic structures affected by high and low flows. Generally, 80% probability of exceedance is recommended so that there is sufficient water, 4 out of 5 years. The 80% probable or available flow for irrigation purposes (flow exceeded in 4 out of 5 years) was obtained from analysis of river flows for RGS 4G01 using standard probability methods. The base flow or 30% of Q95 probable flow (also referred to as the environmental flow) was also computed. The available flow for irrigation is calculated from Q80 (also called the natural flow, as it is exceeded 4 out of 5 times in a year) and the environmental flow (Q95). Values of Q80, Q90 and Q95 are shown in table 2 under section 4. The difference between the environmental and natural flow gives the available water for irrigation. Kenyan regulations require that 30% of the Q95 base flow be considered as the environmental flow. The available water for irrigation is therefore calculated from equation 15. This formula is also called the water balance calculation for irrigation. Low flow analysis data has been presented for exceedance probabilities of 80 and 90% (Q80 and Q95). The Q80 flow is normally considered as the reliable flow for irrigation purposes. For Tana at Garissa, 4G01, the reliable flow varies from 35.7 cumecs in March to 122.6 cumecs in November. The available water is maximum in April-May when the demand is lowest.

1. Introduction

The Tana River is the largest and most important river in Kenya. The total catchment area is 95,918 km2, 16% of Kenya territory. The river longitudinal length is 979 km, between the Kenya Highlands with peak at an elevation of 3,999 m and the Indian Ocean. It originates from Mount Kenya and Nyandarua Ranges with numerous streams networks joining to build its volume as it rolls down in an easterly direction (Kitheka, 2014). The upstream is slightly dammed for water supply purposes but more regulated at the seven folk's dams which are the main sources of hydro-power for the country. Further downstream at the Grand Falls dam site to Kora Rapids, the Tana River flows down about 100 km from an elevation of about 450 m to 200m. On the downstream part (after Garissa), the Tana River flows down about 700 km through a vast alluvial flood plain to finally reach the Indian Ocean. The mainstream has a width of about 100 m and meanders through a flood plain with a width of 3 to 4 km at the delta.

The Tana River Basin can generally be divided into three main sub-catchments based on climatology and water resources availability (Kitheka, 2014). The Upper catchment can be taken as the area upstream of Kamburu water reservoir covering some 9,348 km^2 from the further source point; the Middle catchment between Kamburu reservoir and Kora Rapids

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covering some 15,873 km^2 downstream stream; and the lower sub-catchment downstream of Kora Rapids and after the Tana Grand falls covering some 70,696 km^2 (Geertsma et. al., 2010). The Tana River catchment slopes gently towards the ocean from Garissa a factor that limits design of water storage reservoirs.

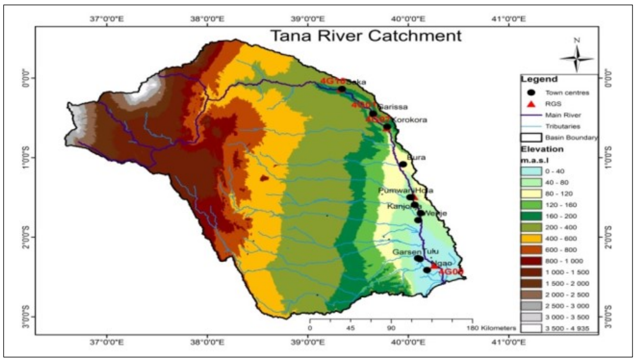

Figure 1: Tana River Catchment

1.1 Objective of the study

The objective of this study is to establish water resources availability for agricultural production in Tana Basin.

1.2 Hydrology and Climate of the Tana Basin

1.2.1 Rainfall characteristics of the basin

The mean annual rainfall in Kenya varies from as low as 200mm in the marginal areas of northern Kenya to as high as 2000mm in the high potential areas. The 600mm isohyet forms the boundary between semi-arid and humid climates while the 300mm isoline delineates the arid from the semi-arid zones. The marginal areas are characterised by high rainfall intensities with associated impacts of soil erosion both by water and wind mainly due to the exposed top soils (Njogu and Kitheka, 2017).

The bi-modal rainfall pattern within the Tana Basin is clearly seen from the mean monthly rainfall distribution as illustrated in Figure 2. In the upper headwater region (formed by the eastern slopes of the Aberdare, Mt. Kenya and Nyambeni mountain ranges, and the elevated parts of eastern Kenya), the volumes of rainfall are generally relatively high. Considerably less precipitation is received within the lower catchment zones covering the central and eastern parts of the catchment, with the exception of the 20 to 40 km wide, relatively humid coastal strip. Within the eastern and central areas of Kenya, which form the main catchment of the Tana Basin, there are two distinct rainy seasons: March-May and October-December. The two separated by a dry period stretching from June to September.

Drought conditions are more pronounced in the lower catchment areas. The second dry spell runs from January to February, and it's again more conspicuous in the eastern parts. Arid conditions prevail in most parts of the lower catchment: generally less than 400 mm of rainfall is received annually (Notter et. al., 2007). About 90% of the precipitation falls during the two wet seasons, with the eastward monsoon seasons being distinctively dry. Mean air temperature range from about 25°C to 27°C in the lowlands and decline with altitude. The mean annual water temperature within streams varies from 12°C to 30°C.

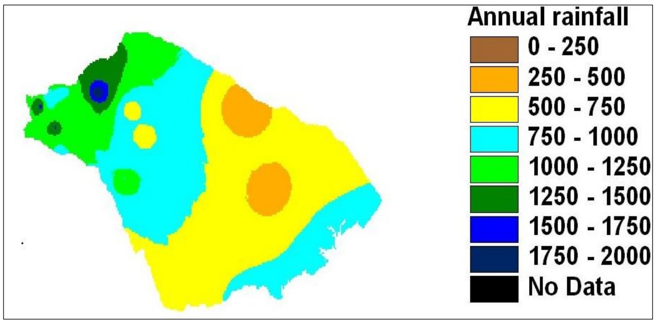

Figure 2: Rainfall distribution- Tana River catchment

Table 1: Tana River Mean Monthly Rainfall and pan Evaporation

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean Rainfall (mm)	28.5	21.6	75.9	201.7	133.6	28.9	24.5	23.1	18.8	92.3	167.3	80.1	1002.2
Mean evaporation (mm)	187.4	185.7	193.2	163.4	158.6	144.1	143.8	156.9	186.5	203.1	163.5	168.2	2054.4
Net loss (mm)	-158.9	-164.1	-117.3	+38.3	-25.0	-115.2	-119.3	-133.8	-167.7	-110.8	+3.8	-88.1	-1052.2

It can be deduced that, it is only during the long rain season and short rain season that a surplus of moisture is attained. All the other months have a deficit of moisture resources and hence the need to harvest water to overcome such deficits.

1.3 Evaporation losses

Evaporation is the primary process of water transfer in the hydrological cycle. The rate of evaporation is dependent on the temperature of the evaporating surface and the ambient air temperature. Evaporation from an open water surface is a function of available energy, the net radiation, the temperatures of surface and air, the saturation deficit and the wind speed. Evaporation from the land surface is a combination of evaporation of liquid water from precipitation collected on the surface, rainfall intercepted by plants and vegetation, and the transpiration by plants. Figure 3 below shows the annual evaporation ranges for the Tana river basin.

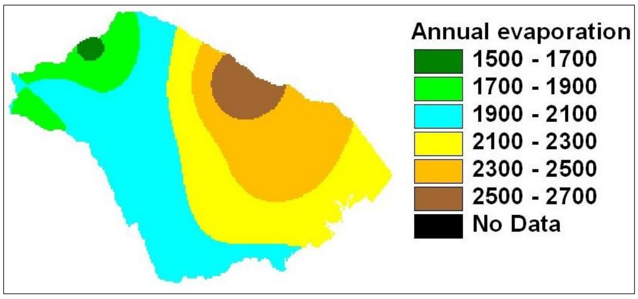

Figure 3: Mean annual evaporation for Tana River Catchment

2. Data and Methodology

2.1 Data

Three sets of data were used in this study. These included;

1) Daily and monthly rainfall records for selected stations in the Tana basins. This data was obtained from the Kenya Meteorological Department.
2) Monthly evaporation records for selected stations in the Tana basins.
3) Daily discharge records for gauging location 4G01 for the Tana basin (Tana at Carissa) were obtained from Water Resources Authority, Kenya.

The data quality control was done to detect any discontinuities that the data may contain. These may occur due to non-natural influences like changes in observational schedules and methods (WMO, 1966).

2.1.1 Estimation of missing data

In this study, the normal ratio method was used. This method was used because the stations of study were neighbouring each other and so using them to estimate missing data for a nearby station would increase accuracy (Little, and Rubin, 2014).

If the stations 1, 2, 3, ….., m have their annual precipitation values as P1, P2, P3,…., Pm respectively and the annual rainfall of a station X, not included in the m stations is missing, then the missing precipitation record for station X, PX can be calculated using the normal ratio method. If the normal precipitation N1, N2, N3, ….., Ni at each of the above stations (M+1) including station X is known, and the and the precipitations are within 10% of the normal precipitation within 10% of the considered gauge (X), then a simple arithmetic average can be followed. Hence:

$$P_X = \frac{1}{M}(P_1 + P_2 + \cdots \ldots P_M) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (1)$$

2.2 Flow Frequency analysis

The analytical approach of estimating the frequency of occurrence of an event uses the concept of theoretical distribution and gives probabilities of occurrences in a population. For flood and drought frequency analysis, the following data can be used;

1) Annual maximum series, which consists of the peak flows of each year.
2) Partial duration series, which consists of peaks exceeding a certain threshold q_0
3) Annual minimum series, which is formed from the lowest flow observed in each year.
4) Annual maximum drought volumes, formed by determining the maximum deficiency of river flow to meet the specified water demand in each year if record at a given location.

2.2.1 Selection of Time Series Distributions

The applicability of the several types of statistical distribution to the modelling hydrological extremes in hydrology is not necessarily obvious, and the use of a particular distribution in any country is often subjective. Two examples in the United States of a standardized application of distributions are the following:

1) the United States Geological Survey (USGS) uses an LP3 distribution to describe annual minimum stream flow series;
2) the National Drought Atlas for the US (Werick 2000) uses a Generalized Wakeby distribution to describe annual minimum stream flow series.

The traditional flood frequency analysis approach has been as a problem in parametric statistical inference, although it is not usually known which distribution the flood event naturally follows.

The magnitude and probable frequency of recurrence of annual maximum floods was studied at some river gauging stations in Kenya (Lugania, 1982), within the major basins of the Nzoia, Tana and Athi rivers. Preliminary flood frequency curves were determined through a comparison of various probability distributions (2-parameter Gamma, Pearson Type III, Log-Pearson Type III, Fisher-Tippet extremal) with the observed flood data using both the annual maximum series (AMS) and the Peaks over Threshold (PoT) methods. With the data base available at that time, it was found that the 2-parameter Log-normal and the 2-parameter Gamma distributions provided the best fit for all three basins.

A comparison of the results of applying the AMS and PoT methods was made for data from East Africa (Mkhandi, 2005), Opere et.al (2006); however the majority of regional frequency analyses have preferred to us the AMS method, which has also been applied for this Project

2.2.2 Fitting extreme value distributions

The distribution parameters are conventionally estimated by the method of moments (MOM), the maximum likelihood (ML) method or the method of probability weighted moments (PWM).
MOM is the simplest calibration method and commonly used; ML has the disadvantage of being much more complex; and PWM is regarded as one of the best methods for parameter estimation.

The probability density functions of the family of extreme value distributions are given by:

$$F(x) = exp(-\left(1+\frac{\Upsilon}{\beta}(x-\alpha)\right))^{-\frac{1}{\gamma}} \quad If\ \gamma \neq 0 \ldots\ldots.(2)$$

$$F(x) = \exp\left(-exp-\left(\frac{x-\alpha}{\beta}\right)\right) \quad If\ \gamma = 0 \ldots\ldots\ldots\ldots.(3)$$

Where γ, α, and β are the shape parameter (extreme value function), threshold value and scale parameter respectively.

1) For γ=0, the distribution is a Gumbel or Extreme Value Type I (EV1) distribution.
2) For γ>0, the distribution is a Fretchet of EV2
3) For γ<0, the distribution is a Weibull or EV3

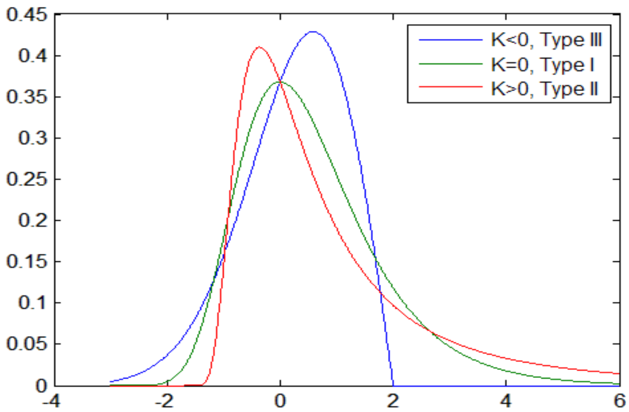

Figure 4: Probability curves for EV1, EV2 and EV3 distributions.

Various tests of goodness of fit can be applied in the selection of a distribution to model extreme events for a particular site, including the chi-square, Kolmogorov-Smirnov, moment ratio diagrams, regional behavior of statistics, and quantile-quantile plots.

2.2.3 Calculation of Return period discharges

The return period T is a function of the GEV function.

$$T(number\ of\ years) = F(\Upsilon, \beta, \alpha) \ldots\ldots\ldots\ldots.(4)$$

T is therefore calculated using the parameters obtained in the distribution that corresponds to the tails. If F(x) represents the distribution of the annual maximum series, the return period T can be calculated as follows.

$$T(number\ of\ years) = \frac{1}{1-F(x)} \ldots\ldots\ldots\ldots\ldots (5)$$

Hence,

$$F(x) = 1 - \frac{1}{T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where, $1 - F(x)$ is the population survival function

The inverse distributions are given by;

$$x = \alpha + \frac{\beta}{\gamma}\left(1 - \left(In(F(x))\right)^{\gamma}\right) \text{ for } \gamma \neq 0 \ldots\ldots\ldots\ldots (7)$$

$$x = \alpha + \beta(-In(-InF(x))) \text{ for } \gamma = 0 \ldots\ldots\ldots\ldots\ldots (8)$$

The parameters obtained were used in the extreme value distribution equations using specified values of T.
The results were the discharges corresponding to each return period for each gauging site.

2.2.4 Flow duration curves

A flow duration curve indicates the percentage of time the river discharge (daily, monthly etc.) was exceeded over a given period.
Flow duration is represented by empirical exceedance frequency E, which is given by:

$$E(\%) = \frac{100t}{s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Where 't' represents the stream flow rank (flow records sorted in descending order), and 's' is the sample size considered.

The exceedance frequency for high flows can then be calculated as

$$E(\%) = \left(\frac{100t}{s}\right)\frac{1}{1-G(x_E)} \ldots\ldots\ldots\ldots\ldots (10)$$

Where x_E is the exceedance level.

The exceedance frequency for high flows with an exponential distribution is therefore given by:

$$E(\%) = \left(\frac{100t}{s}\right)\left[\exp\left(\frac{x-x_t}{\beta}\right)\right]^{-1} \ldots\ldots\ldots\ldots (11)$$

The E-percentage event can then be calculated as:

$$x_E = x_t + \beta\left[\frac{\ln\left(\frac{100t}{s}\right)}{\ln(E)}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Where 't' is the number of observations above the threshold, s is the sample size, β the location parameter and xt the threshold.

2.2.5 Low flows

Low flows are the limiting factor for off-river supply of irrigation schemes. In accordance with Kenya's regulations, it is suggested that the supply reliability for irrigation purposes be 80%, ensuring that a minimum flow can be abstracted at least in 4 out of 5 years. Low flow analysis involves evaluation of return periods and the probability of exceedance. Both of these require the lowest flow during a particular time period to be computed.

Two methods can be used to extract low stream flows from discharge series: the annual minimum series, and the PoT method. The annual minimum series are based on the lowest flow values in each year of record, and is usually applicable for long data series (over 50 years). The PoT method specifies a threshold below which all stream flows are considered 'low' flows, and in this case the probability of exceedance of between 70% and 99% are normally considered. In this analysis the low flow frequency method has been used. Low flows are constructed from a series of annual minima, with the available stream flow data being extrapolated by a theoretical distribution to improve the accuracy of the estimation.

The annual minimum values were transformed into high values by using X=1/x and these transformed (high) values then sorted in descending order of magnitude and the recurrence interval calculated. For the probability distribution of the extremes below a threshold xt in n period of years, the return period, T, of low stream flows was calibrated by using the following equation

$$T_c = \frac{n}{t} * \left[\frac{1}{\exp\left(-\left(\frac{x^{-1} - x_t^{-1}}{\beta}\right)\right)} \right] \dots\dots\dots\dots\dots\dots (13)$$

Where T_c is the calibrated return period in years based on the exponential Extreme Value distribution and β the extreme value parameter

The design stream flow for a certain return period was estimated on the basis of linear regressions in the exponential quantile plots;

$$X_T = x_t^{-1} + \beta \left(\ln(T) - \ln\left(\frac{n}{t}\right) \right) \dots\dots\dots\dots (14)$$

Where X_T is the estimated design low stream flow at the return period T years, x_t is the threshold value below which all stream flow are low flows, 'n' is the years of record, and 't' is the number of extracted low stream flows

2.2.6 Available water for irrigation

Available water for irrigation is estimated from the low flow analysis by computing the probabilities of exceedance. The assessment of available flow for irrigation can be estimated by deducting the following from the Q80 probable flow:

Deduction of estimated existing / future abstractions – this can be determined from available information on irrigation activities along the Umba river.

Deducting the environmental flow - this is normally taken as 30% of Q95 probable flow.

Generally 80% probability of exceedance is recommended so that there is sufficient water, 4 out of 5 years. The 80% probable or available flow for irrigation purposes (flow exceeded in 4 out of 5 years) was obtained from analysis of river flows for RGS 3KG01 using standard probability methods. The base flow or 30% of Q95 probable flow (also referred to as the environmental flow) is also computed.

The probabilities of exceedance are used to estimate the water available for irrigation at the different gauged stations in the catchment. The available flow for irrigation and the environmental flow are crucial in this process. The available flow for irrigation is calculated from Q80 (also called the natural flow, as it is exceeded 4 out of 5 times in a year) and the environmental flow (Q95). Values of Q80, Q90 and Q95 are shown in table 2 under section 4. The difference between the environmental and natural flow gives the available water for irrigation. Kenyan regulations require that 30% of the Q95 base flow be considered as the environmental flow. The available water for irrigation is therefore calculated from equation 15. This formula is also called the water balance calculation for irrigation.

$$Available\ water\ for\ irrigation = Q80 - 0.3 * (Q95) \dots\dots\dots (15)$$

3. Results and discussion

The results of analyses carried out are presented in this section

3.1 Time series analysis

From the time series plot of the available data shown in figure 5, two major peaks are discernible centred around 1962 and 1968. Figure 5 below shows the mean annual discharge for station 4G01 from the year 1941 to 1995.

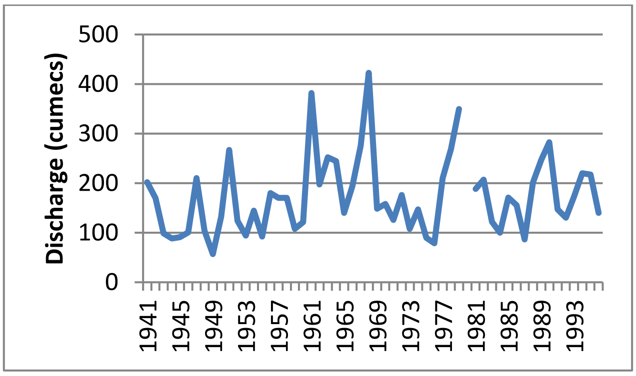

Figure 4: Mean annual discharge for 4G01

Table 2: Monthly Flow (m3/s) statistics for RGS 4G01

Month	Mean	Median
JAN	130.450	93.688
FEB	85.421	73.393
MAR	87.974	71.140
APR	248.942	173.357
MAY	362.810	323.858
JUN	204.731	195.715
JUL	115.248	112.611
AUG	89.712	90.495
SEP	75.743	77.230
OCT	97.276	77.299
NOV	294.765	193.243
DEC	239.894	163.700
Annual Mean Flow is 170.0 m^3/s		

In table 2; a maximum mean monthly flow of 362.8m3/s is observed in May while the minimum of 75.7 m3/s occurs in September. This a substantial flow to support irrigation

3.2 Flood frequency analysis

The results of frequency analyses using EV1 and GEV distributions for different methods of parameter estimation are presented in table 3 for various return periods ranging from 5 years to 1000 years. The results show some consistency in the flood estimates from the two distributions and therefore either could be used for flood estimate for this location.

Table 3: Results of flood frequency analysis for RGS 4G01

Station	Return periods									
	5	10	20	50	80	100	500	750	900	1000
4G01	EV1-Mom (u = 61.292 a = 26.08)									
	100.41	119.98	138.76	163.06	175.41	181.26	223.34	233.93	238.69	245.10
	EV1-MLE (u = 61.196 a = 25.653)									
	99.67	118.93	137.39	161.29	173.45	179.21	220.60	231.01	235.69	239.89
	EV1-PWM (u= 60.842 a = 26.859)									
	101.13	121.29	140.62	165.65	178.37	184.40	227.74	238.63	243.54	247.11
	GEV-MLE (u = 60.607 a = 25.213 k = -0.429)									
	99.67	120.17	140.47	167.69	181.96	188.81	240.11	253.58	259.71	265.86
	GEV-PWM (u = 60.526 a = 26.448 k = -0.0207)									
	100.82	121.45	141.55	168.02	181.67	188.19	235.93	248.19	253.73	260.49

For the purpose of available water for irrigation, mean monthly flows have been used to estimate flow magnitudes corresponding to specific probability of exceedance as shown in table 4.

Table 4: Summary of Exceedance probability and mean monthly flow for 4G01

Exceedance prob. (%)	Q95	Q90	Q85	Q80
Mean monthly flows (m3/s)	39.92	50.41	61.21	68.34

From table 4 above, the available flow corresponding to 80% probability of exceedance can be seen to be 68.34m3/s. The environmental flow corresponding to 95% probability of exceedance is estimated at 11.0m3/s.

The plots of the flood frequency analyses for this location using various types of distributions are shown in figure 6 below.

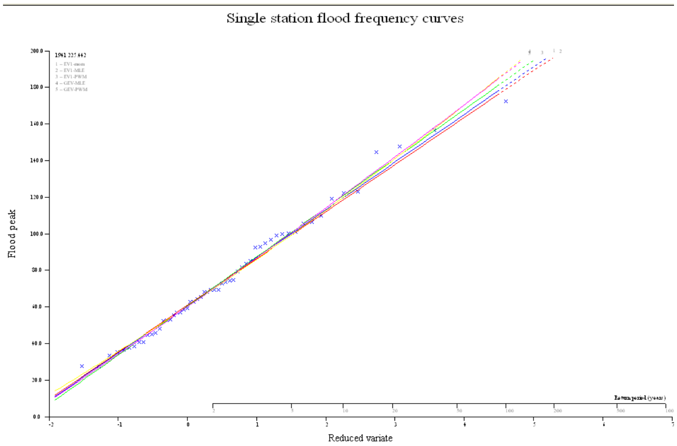

Figure 5: Flood frequency curves for 4G01

3.4 Low flow analysis

The results of low flow analysis using different distribution fit are shown in figure 7 and table 5. Again the results show some high level of consistency.

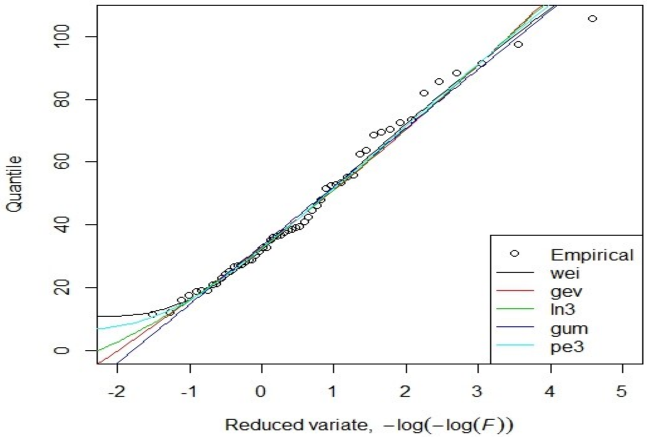

Figure 7: Low flow frequency analysis curve for Tana at Garissa (4G01)

Table 5: Low flow analysis at 4G01

T (years)	wei	gev	ln3	gum	pe3
2	39.189	39.463	39.396	40.322	39.261
5	23.517	24.690	24.441	24.551	23.950
10	18.259	18.645	18.557	17.846	18.396
20	15.260	14.289	14.482	12.920	14.884
50	13.077	9.946	10.607	7.924	11.924
100	12.164	7.327	8.383	4.870	10.445
200	11.608	5.098	6.567	2.245	9.382

3.5 Available water for irrigation

In this section, low flow analysis results have been presented for exceedance probabilities of 80 and 90% (Q80 and Q95). The Q80 flow is normally considered as the reliable flow for irrigation purposes and low flow analysis results presented in table 6 and shown in figure 8.

Table 6: Available flows (Q80 and Q95) at RGS4G01

4G01			
	Q80	Q95	**Available water for irrigation**
JAN	66.188	17.311	60.99
FEB	44.166	10.729	40.95
MAR	35.696	14.356	31.39
APR	92.283	47.190	78.13
MAY	159.347	12.245	155.67
JUN	114.518	8.772	111.89
JUL	80.536	5.568	78.87
AUG	65.602	4.513	64.25
SEP	52.434	5.148	50.89
OCT	57.400	4.585	56.02
NOV	122.640	31.245	113.27
DEC	104.939	13.453	100.90

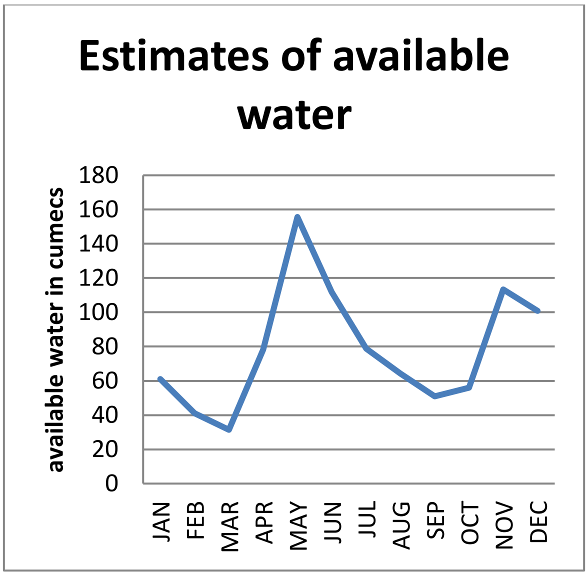

Figure 8: available water at 4G01

Conclusion

The available water for irrigation shown in table 6 above can be compared against the estimates of crop water requirement especially during the dry season flows to determine the sufficiency to support irrigation.

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