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Low Flow Characterization of a Coastal River in Ghana

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Abstract: *Various probability distribution functions including Normal, Lognormal, Weibul, Gumbel and Gamma distributions were fitted to the mean daily low streamflows for the coastal river Ayensu in Ghana to characterize the low flow regime of the river. The Normal and Gumbel distributions produced the best fit with NSE equaled to 99.17% and 99.19%, respectively. A Flow Duration Curve was developed and used to determine the minimum flow threshold for the Ayensu River using mean daily streamflow series at Okyereko gauging station. Results showed that streamflow in the basin at Okyereko had little tendency to produce unusual extreme low flow with the minimum flow threshold value of 0.20 m³/s which is equaled or exceeded 95% of the time. The probability of occurrence of low extreme flows in the basin is low and that water abstraction in terms of use for water supply for domestic, industrial and agricultural requirement is considered reliable and sustainable.*

Keywords: *Low flow, flow duration curve, Weibul-Gumbel distribution, Ayensu river basin, Ghana*

I. Introduction

Low streamflow statistics, according to [1], indicate the probable availability of water in streams during times when conflicts between water supply and demand are most likely to arise. Because of this, low streamflow statistics are needed by the state, regional and local agencies for water-use planning, management and regulatory activities for a variety of water resources application. These activities include (i) developing environmentally sound river-basin management plans, (ii) siting and permitting new water withdrawals, inter-basin transfers and effluent discharges, (iii) determining minimum streamflow thresholds for the maintenance of aquatic biota and (iv) land-use planning and regulation. Continuous water supply demands continuous abstraction from the surface and ground water bodies. In abstracting water from rivers, consideration should be given to the minimum flow needed to sustain the stream. Also, it is important to determine the reliability of streams to water supply during the dry seasons where the amount of river flow is low.

Estimation of low streamflow statistics at gauged river sites involve evaluation of annual n-day minimum streamflow, description of annual minimum streamflow through the selection of a probability distribution and the estimation of the distribution's parameters [2]. Low flow conditions of a stream may be described by several low streamflow characteristics in the form of indices and exceedance percentile. Depending on the type of data initially available and the type of output information required, there exist different methods for estimating low-streamflow indices. These include Flow Duration Curve (FDC), Low Streamflow Frequency Analysis (LSFA) and Flow Distribution Functions (FDF).

Studies [3] conducted on water resources in Ghana showed that the country is endowed with sufficient surface water resources to serve all its water needs. However, there is the need for a gradual process of development and conservation to make the water available in sufficient quantity and good quality [3],[4]. Yet in the dry seasons some rivers dry up and hinder certain water uses such as agriculture, domestic water supply, navigation and hydropower generation. Thus low flow statistics are needed to determine the availability of water for water supply, waste discharge and power generation. According to [5], the assessment of low streamflow is important because it is a critical index for these water projects. The Ayensu River being part of the Coastal river systems of Ghana, is being characterized because of its economic importance [6]. According to [6] a baseline survey conducted in 1997 in the Ayensu basin identified inadequate water supply as one of the problems facing the irrigation scheme. Furthermore, [7] established that water delivery flexibility index for the project area was 5 and tail-end supply ratio of 0.45 was noted. Further [8] reported a high water stress/vulnerability index for the basin beyond 2020.

Thus, this paper sets out to use the probability distributive functions namely, Gumbel, Weibul, Log-normal, Gammaand normal to model the low flow regime of the river to establish the best fit to characterize the low flow regime. This will enable the properties of flow for the river to be established to compliment better management of the basin.

II. Study Area

The Ayensu river basin (Figure 1) is part of the Coastal river system of Ghana with an area of approximately 171 km^2 and length of 98km^2 [9]. It lies between latitudes 5^{o}20'N to 6^{o}05'N and longitude 0^{o}30'W to 0^{o}50'W. The main tributary of the river is Akora [10]. The basin is located in two climatic regions; i.e. the wet Semi-Equatorial in the northern.

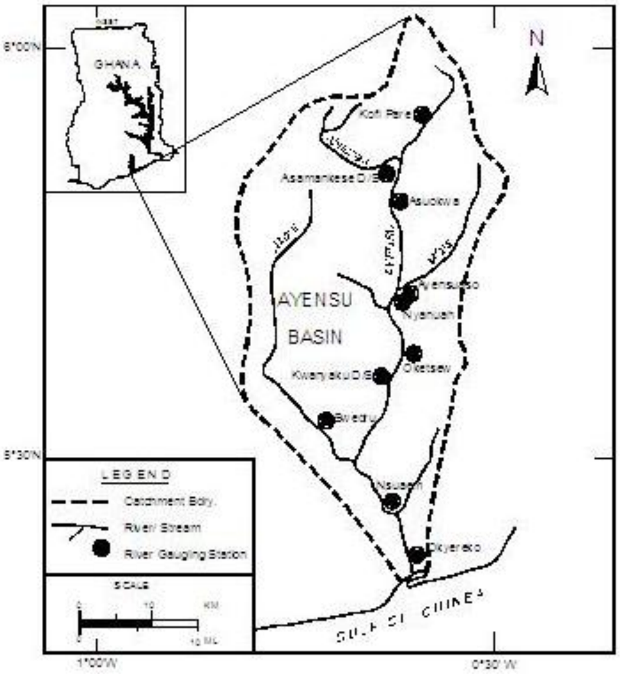

Figure 1: Map of Ayensu River Basin

Part and the dry Equatorial in the south. Rainfall in the basin is seasonal, with two rainfall peaks in June and September, where dry periods span between December and March. However, the dry Equatorial region has mean annual rainfall less than 900 mm while the wet Equatorial has a mean annual rainfall between 1200 mm and 2000 mm [10]. The Ayensu river is perennial suggesting that groundwater plays a very important role in its existence. This ground water resource in Ayensu river basin is fresh [11]. The dominant soil type is forest ochrosols, which covers about 95% of the area. The other soil type is savannah ochrosols and savannah lithosols in the southern part of the basin. Three vegetations types are found in the basin. The upper and the middle parts are covered by moist semi-deciduous forest. The remaining third of the basin is coastal thickets and grasslands. The mean annual stream flow [9] is 8.27m³/s with maximum flows occurring between june-july with mean annuals of 20.89-22.40 m³/s. Annual runoff is estimated [9] to be 268 million m³/s.

The Ayensu river basin habours two important water schemes. i.e. the Okyereko Irrigation scheme and the Kwanyako Water Supply System (Kwanyanko Headworks Project) in the Central Region. The dam and water supply system at Kwanyanko was established in 1964 to supply treated water for the surrounding communities. It was rehabilitated in 1998 and 2005 which increased the total water supply capacity of the system from 12,440 m^3/day to 35,000 m^3/day [12]. Currently the system serves 13 towns and 160 surrounding communities including Cape Coast in five (5 No.) districts in the Central Region at an average production rate of 90,000 m³of water per day. The Okyereko Irrigation Scheme was constructed between 1973-1982 and rehabilitated (1996-2004) as a pilot scheme under the Small-Scale Irrigated Agriculture Promotion Project (SSIAPP) to support local agriculture in the basin.

III. Methodology

Statistical analyses which according to [13] are widely applied to derive indices to characterize low streamflow regimes are the main tools used to characterize the coastal catchment. All analyses were done in MS Excel.

3.1 Streamflow data

The basic data used for the study was the mean daily streamflow data series collected from the Ayensu basin at the Okyereko river station in Ghana. This data set was used because of its relatively good data length and continuity compared to the other stations within the basin. Available streamflow data from the station were from 1962 – 1997. They were obtained from the Hydrological Service Department (HSD) of the Ministry of Water Resources, Works and Housing (MWRWH), Accra.

3.2 Estimation of Low Streamflow

The duration of streamflow data for the study was less than 50 years, thus the peak-over threshold method [14] was adopted to define the minimum flow requirement of the river. The threshold value below which all streamflows are minimum was estimated from the flow duration curve (FDC) at 95 % probability of exceedance. The FDC for the river using the complete data series was developed and then used to extract the low streamflows at probabilities of exceedance of 95% and above.

3.3 Flow Duration Curve

A Flow Duration Curve (FDC) defines the relationship between any given discharge value and the percentage of time that this discharge is equaled or exceeded [15], [16]. The FDC is developed by plotting all ranked streamflows against their rank, expressed as the percentage of the total number of time steps in the record [15].

Ranked numbers were assigned to each streamflow value with the largest flow ranked as 1 and the smallest *n*, where *n* is the total number of records. The probability of exceedance was computed using the relation in equation (1) [14]:

$$P = 100 \times \frac{r}{n+1} \qquad (1)$$

Where *P* is the percentage of time a given flow is equaled or exceeded, *n* is the total number of records and *r* is the rank of the flow magnitude. The FDC was obtained by plotting ranked streamflows against their rank, expressed as the percentage of the total number of time steps in the record.

3.4 Extraction of Low Streamflow

The next step was to extract the low streamflow from the ranked (or sorted) flows. The extraction was done in the Microsoft Excel Worksheet by selecting, copying and pasting in a new column the streamflows that were equaled or exceeded 95 % of the time (i.e. from 95 % to 100 % probability of exceedance).

3.5 Estimation of Baseflow Contribution

Baseflow contribution to streamflow in the basin was estimated using equation (2) with the complete flow series [17]:

$$\mathrm{f_b} = \frac{\mathrm{Q_{90}}}{\mathrm{Q_{50}}} \qquad (2)$$

where f_b is the fraction of baseflow contributed to low streamflow and Q_{50} and Q_{90} are the streamflows which are equaled 50 % and 90 % of the time, respectively.

3.6 Flow Frequency (Return period) Analysis

In developing the flow frequency curve, the mean daily low river discharges for the period of record were transformed into high values by using the transformation (X=1/x). The transformed values were sorted in descending order of magnitude and assigned rank numbers with the largest value ranked as *1* and the lowest *n*, where *n* is the total number of record data. The recurrence interval of the streamflow with certain magnitude was computed using equation (3). The streamflow frequency curve was developed by plotting the flow discharge against the empirical return period. The return period for extremes low flow values was also computed using equation (3) [18] [19]:

$$T_c = \frac{n}{t} * \left[\frac{1}{exp\left(-\left(\frac{x^{-1} - x_t^{-1}}{\beta}\right)\right)}\right] \qquad (3)$$

On the basis of linear regressions in the exponential quantile plots, the design low streamflow for certain return period (T-years) was estimated by re-arranging equation (3) into equation (4) [18, 19], i.e.

$$x_T = x_t^{-1} + \beta(\ln(T) - \ln\left(\frac{n}{t}\right)) \qquad (4)$$

where x_T is the estimated design low streamflow at T-years, x_t is the threshold value below which all streamflows are low flows, *T* is the return period in years, *n* is the period of record (in years), *t* is the number of extracted low streamflows and *β*, the calibrating parameter.

3.7 Flow Distribution Functions

The Normal, Log-normal, Weibul, Gumbel and Gamma distribution functions were used based on their common use in several literatures. The type of flow distribution for the basin was identified by calibrating and validating the distribution parameters and selecting the function that best fits the streamflow.

3.7.1 Calibration and Validation of Data Sets

In order to calibrate and validate the parameters of the distribution functions, two sets of flow data were required. Streamflow values that equalled or exceeded 90 % of the time were extracted to acquire more data for analysis in this section. The calibration and validation data sets were obtained by splitting the extracted mean daily low streamflows into two. The splitting of the data was done by first randomizing the low streamflow data so that both the calibration and validation data sets would have the same range of data sets. This was achieved in Microsoft Excel by using the ***RAND()*** function and following the steps below:

(i) The extracted low flow values were entered into a new column in Microsoft Excel Worksheet
(ii) The *rand()* function was entered in the next column
(iii) The *rand* values were selected and sorted (either ascending or descending) by *expanding the selection*.

The randomly sorted low streamflows were then split into two data sets, calibration and validation data sets.

3.7.2 Fitting Normal Distribution to Mean Daily Low Streamflows

The function ***NORMDIST(x, μ_x, σ_x, 1)*** was used to estimate the probability of exceedance $F_e(x)$ of a normal distribution function using equation (5).

$$F_e(x) = 1 - NORMDIST(x, \mu_x, \sigma_x, 1) \qquad (5)$$

The initial parameters of the distribution, μ_x and σ_x, were estimated from the low streamflows using equations (6) and (7), respectively.

$$\mu_x = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (6)$$

$$\sigma_x^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu_x)^2 \qquad (7)$$

3.7.3 Fitting Lognormal Distribution to Mean Daily Low Streamflows

The ***NORMDIST (lnx, μ_{lnx}, σ_{lnx}, 1)*** function was used to evaluate the cumulative distribution function $F_e(x)$ of a log-normal distribution function using equation (8).

$$F_e(x) = 1 - NORMDIST(lnx, \mu_{lnx}, \sigma_{lnx}, 1) \qquad (8)$$

The initial parameters of the distribution, μ_{lnx} and σ_{lnx}, were estimated from the low streamflows using equations (9 and (10), respectively.

$$\mu_{lnx} = \frac{1}{n}\sum_{i=1}^{n} lnx_i \qquad (9)$$

$$\sigma_{lnx}^2 = \frac{1}{n-1}\sum_{i=1}^{n}(lnx_i - \mu_{lnx})^2 \qquad (10)$$

3.7.4 *Fitting Gamma Distribution to Mean Daily Low Streamflows*

From equation (11), the ***GAMMADIST(x, λ, k, 1)*** [14] function was used to evaluate the cumulative .distributive .function of the gamma distribution function $F_e(x)$. The initial guess distribution parameters λ *and* k were estimated from the mean, μ and standard deviation, σ of low streamflows using equations (12) and (13), respectively.

$$F_e(x) = 1 - GAMMADIST(x, \lambda, k, 1) \qquad (11)$$

$$\mu_x = \frac{k}{\lambda} \qquad (12)$$

$$\sigma_x^2 = \frac{k}{\lambda^2} \qquad (13)$$

3.7.5 *Fitting Weibul Distribution to Mean Daily Low Streamflows*

The probability of exceedance, $F_e(x)$ of a Weibul distribution function was evaluated using equation (14) [14]:

$$F_e(x) = exp\left[-\left(\frac{x}{\beta}\right)^{\tau}\right] \qquad (14)$$

The initial parameters of the distribution, τ and β, were estimated from the mean, μ_x and standard deviation, σ_x of low streamflows using equations (15) and (16), respectively [14].

$$\tau = \mu_x \qquad (15)$$

$$\beta = \sigma_x \qquad (16)$$

3.7.6 *Fitting Gumbel Distribution to Mean Daily Low Streamflows*

The probability of exceedance, $F_e(x)$ of a Gumbel distribution function was estimated using equation (17). The initial parameters of the distribution, *xt* and β, were estimated from the mean, μ_x and standard deviation, σ_x of low streamflows using equations (18) and (19, respectively [14].

$$F(x) = 1 - exp\left[-exp\left(-\frac{x - x_t}{\beta}\right)\right] \qquad (17)$$

$$\mu_x = x_t + 0.577216\beta \qquad (18)$$

$$\sigma_x^2 = \frac{\pi^2}{6}\beta \tag{19}$$

3.8 Plotting Formula

The Weibul-Gumbel plotting position (Eq. 20) was used because it has more statistical justification and is the commonly used in hydrological frequency studies [14].

$$P = \frac{r}{n+1} \tag{20}$$

Where *P* is the probability that a given streamflow is equaled or exceeded, *r* is the order number of rank and *n* is the total number of records.

Once the data series was identified ranked and the plotting positions estimated, a graph of low streamflow against probability of exceedance was plotted to graphically fit a distribution function. The various distribution functions were fitted to the extracted mean daily low streamflows from the river basin. Distribution parameters were calibrated and validated with the extracted low streamflows. These were compared with the sample data to graphically observe the distribution that produced the best fit to the low streamflows in the basin.

3.9 Parameter Estimation and Optimization Technique

The accuracy or goodness of the estimated parameters was checked through the use of two main optimization techniques. These were the Root Mean Squared Error (RMSE) and the related normalization, the Nash–Sutcliffe Efficiency (NSE) [20] which according to [21] and [22] is widely used in appraising model performance: These criteria are defined as

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} E^2}{n}} \tag{21}$$

$$NSE = 100 * \left(1 - \frac{\sum_{i=1}^{n} E^2}{v.n}\right)\% \tag{22}$$

$$= 100 * \left(1 - \frac{RMSE^2}{v.n}\right)\% \tag{23}$$

where *n* is the number of errors, *v* is the sample variance and *E* is the difference between the Weibul plotting position and the calibrated plotting positions of the distribution functions [14]. During calibration, the parameters were optimized for values which minimize the RMSE or maximize the NSE. This was achieved by using the *solver* tool in Microsoft Excel.

IV. Results and Discussions

4.1 Streamflow data

The streamflow data collected from the Ayensu basin at Okyereko is plotted (Figure2) and from this low flows were extracted. Two peak flows are usually observed (Figure 3) in the basin annually and are separated by periods of low flows with long duration. This could be as a result of the bi-modal nature of rainfall in the southern sector of the country where the Ayensu river is located.

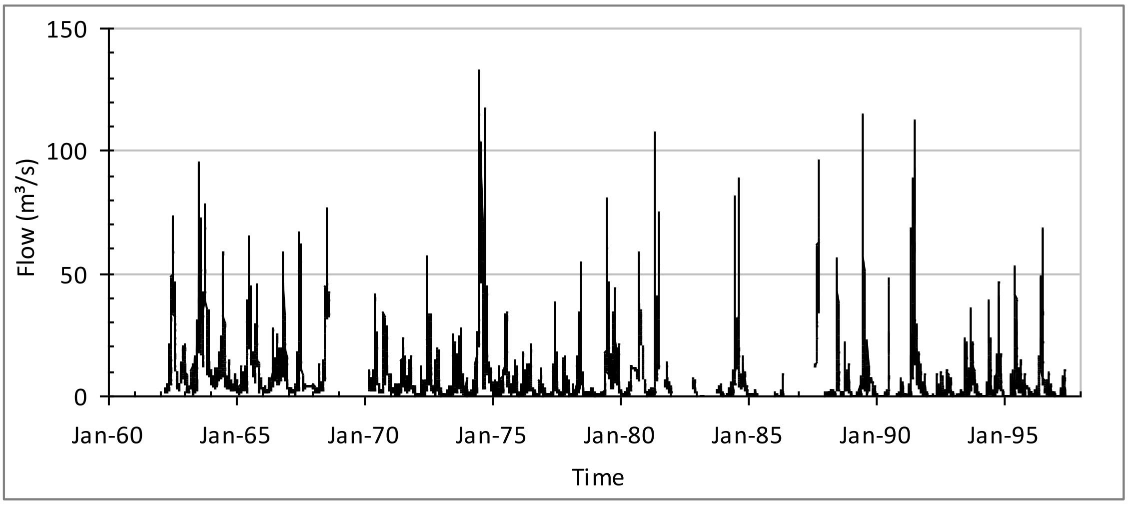

Figure 2: Streamflow series at Okyereko (1962 – 1997)

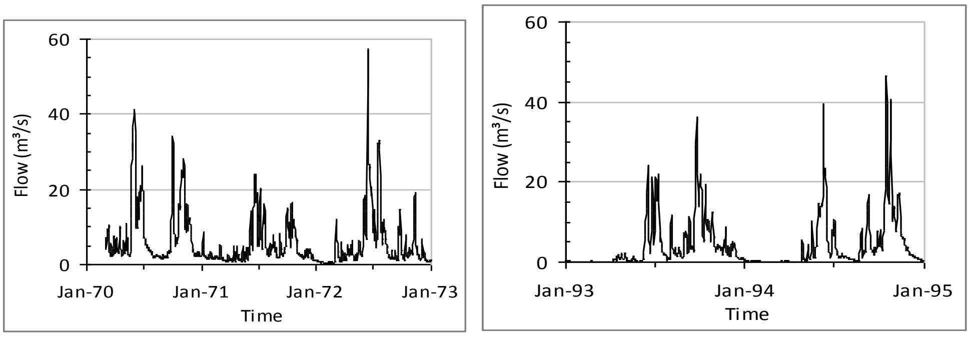

Figure 3: Fractions of historical flows at Ok yereko showing the bi-modal nature of peak flows as a result of the effect of the bi-modal nature of rainfall in the southern sector of Ghana

4.2 The Flow Duration Curve and Minimum Streamflow Requirement

The mean daily low streamflows threshold value for the period of record at 95 % probability of exceedance corresponded to 0.20 m³/s (Figure 4) from the FDC and this corresponded with [9] results for the basin.

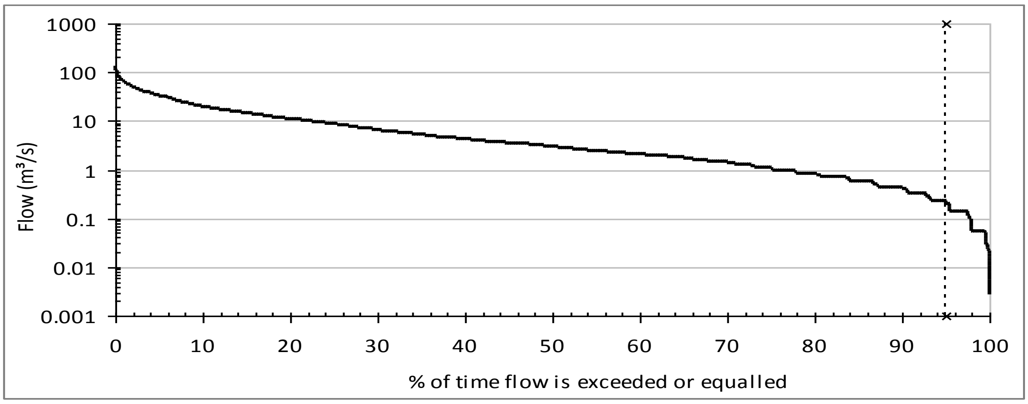

Figure 4: Flow duration curve developed for the Ayensu Basin at Okyereko using mean daily flow series.

4.3 Baseflow Index and Zero Flows

From analysis, (section 3.8) the estimated baseflow index for the period of observation was approximately 0.14 at Okyereko. This index indicated that groundwater contributed approximately 14 % to streamflow in the basin at Okyereko. This value suggested that storage of groundwater within the basin was very low. This might be due to the storage material in the basin having low permeability.

4.4 Flow Frequency (Return Period) Curve and Recurrence Intervals

Figure 5 shows the calibrated and extrapolated return period plot at Okyereko based on the exponential Extreme Value Distribution (EVD). The calibrated parameters for the river are tabulated in Table 1. From the return period plot, streamflow value of 0.100 m³/s is estimated to occur at least once every year in the basin at Okyereko. Similarly, low streamflows with magnitudes 0.016 m³/s, 0.010 m³/s and 0.009 m³/s are expected to occur at least once in a 10-year, 50-year and 100-year period, respectively.

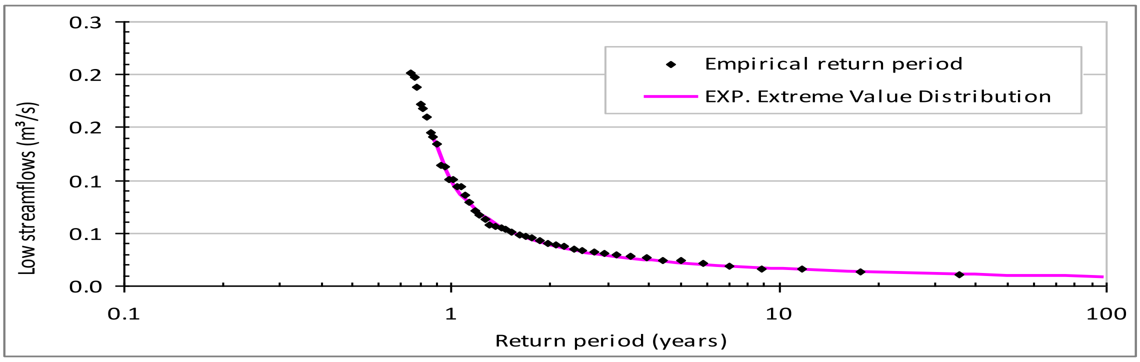

Figure 5: Return period plots for the Ayensu River Basin using low streamflows at Okyereko

Table 1: Parameter Estimates

Parameters	
Number of years of data (n)	20
Number of extracted low flows (t)	156
Threshold of low streamflow (x_t), m³/s	0.751
Calibrating parameter (β)	1.94

4.5 Reliability of the Okyereko River to meet future demand and supply

In Figure 6, the comparative plot between the mean monthly river flow pattern, low flow threshold line at 95 % probability of exceedance and the current water production line at Okyereko is shown. The minimum flow in the basin occurred between December and April and that the lowest flow value of 82,980 m³/day was equaled or exceeded 77.4% of the time. This value is 380 % and 860 % more than the low flow threshold value of 17,280 m³/day and the 1-year return period flow value of 8,640 m³/day, respectively, at Okyereko. However, in the month of February, the current daily water production rate (90,000 m³/day) in the basin exceeded the mean monthly flow in the basin at Okyereko by 8.5%. The flow in the Ayensu basin at Okyereko can therefore be considered sustainable and reliable in terms of use for water supply for domestic, industrial and agricultural use for the period of ten (10) months, starting from March to December (Figure 6).

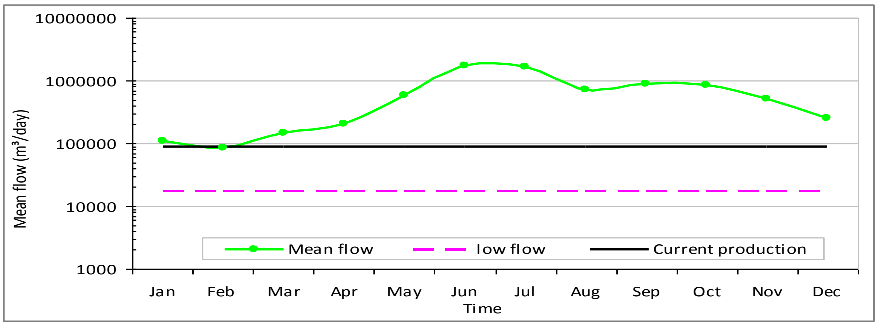

Figure 6: Graph showing the daily mean river flows in the basin, low flow line at 95% probability of exceedance and current water production line at Okyereko

4.6 Fitting flow distribution functions

Figure 7 shows the plots of the calibration and validation of low streamflow data sets for the river station. Mean daily flow data from different stations within the basin were not available for reasonable comparison to be made on which of the distributions best fitted the low streamflows in the river basin. Hence, the discussion and conclusion were based on the results obtained from streamflow data series from the Okyereko station only. Table 2 shows the values of the initial estimate and the final optimized distribution parameters for the respective distribution functions.

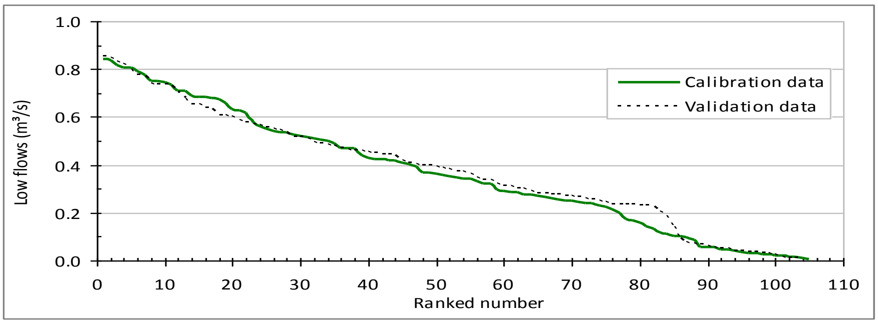

Figure 7: Calibration and Validation low streamflow data for the Ayensu Basin at Ok yereko

Table 2: Optimization of calibrated parameters for the distribution functions

Distribution functions	**Parameters**	**Initial estimate**	**Optimized estimate**
Normal	μ_x, (m³/s)	0.37	0.36
	σ_x, (m³/s)	0.24	0.27
Log-normal	μ_{lnx}, (m³/s)	-1.42	-1.12
	σ_{lnx}, (m³/s)	1.18	0.79
Weibul	β, (m³/s)	0.37	0.44
	τ, (m³/s)	0.24	1.40
Gumbel	β, (m³/s)	0.04	0.24
	x_t, (m³/s)	0.35	0.26
Gamma	λ, (s/m³)	-0.14	1.68
	K	0.20	0.24

Plots of the calibrated distribution functions fitted to the mean daily low streamflows from the basin at Okyereko (Figure 8). Graphically the distribution functions fitted well with the low streamflows except for the extreme ends which was over-estimated. However, with NSE of 99.17 % and RMSE of 0.0265 m³/s the Normal distribution best fitted the mean daily low streamflows in the Basin at Okyereko. This was followed by Gumbel, Weibul, Gamma and lognormal distributions in that order.

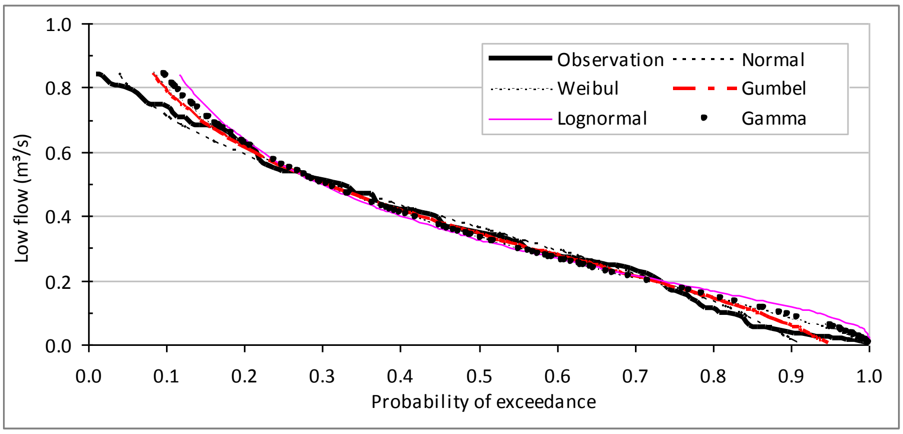

Figure 8: Calibration of distribution parameters using daily low flows from the Ayensu basin at Okyereko

It is also observed that the distribution functions fitted well with the observed mean daily low streamflows under validation mode (Figure 9) with the Normal distribution performing best with NSE of 98.87 % and RMSE of 0.305 m³/s.

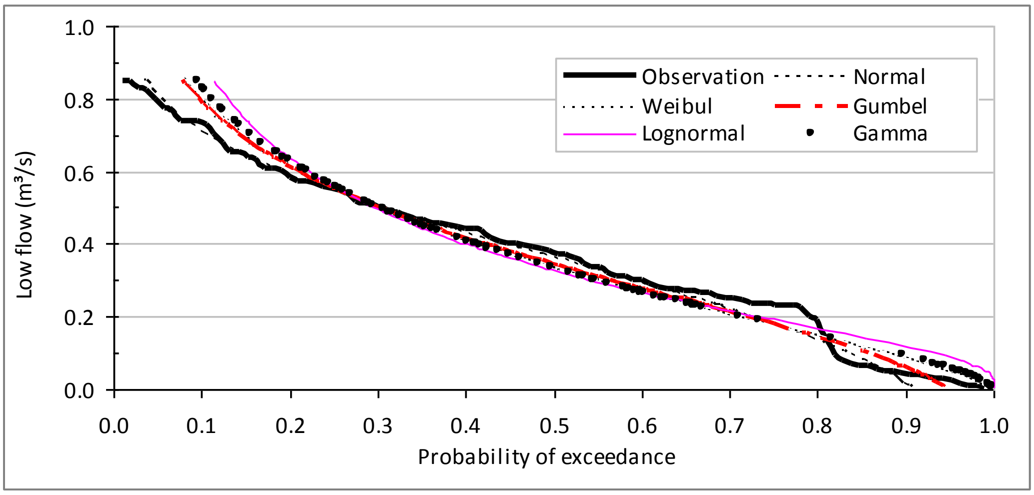

Figure 9: Validation of distribution parameters using daily low flows at Okyereko

Generally, the distribution functions fitted very well with the mean daily low streamflows but showed deviations at the extreme ends of the distributions. Apart from the Normal distribution, all the distribution functions under calibration and validation modes produced higher estimates at the extreme (lower and upper) ends of the mean daily low streamflows. This might have given an upper hand to the Normal distribution in the analysis, hence, the highest NSE and the lowest RMSE values as tabulated in Table 3.

Table 3: Statistical analysis using NSE and RMSE

Distribution functions	**Calibration**		**Validation**	
	NSE (%)	**RMSE (m³/s)**	**NSE (%)**	**RMSE (m³/s)**
Normal	**99.17**	**0.0265**	**98.87**	**0.0305**
Log-normal	96.17	0.0568	94.78	0.0657
Weibul	98.43	0.0363	96.98	0.0499
Gumbel	99.19	0.0261	97.97	0.0409
Gamma	97.95	0.0415	96.22	0.0559

V. Conclusion

The determination and establishment of minimum flow of streams is not only important to water users, but also very crucial for planning water supplies, managing water quality, assessing the impact of prolonged droughts on aquatic ecosystems, among others. Low flow study is essential since it educates stream users on the desirable minimum flow needed to sustain in stream uses.

Streamflow values of 0.20 m^3/s was estimated from the FDC at 95 % probability of exceedance as the minimum sustainable streamflow (low flow threshold) for the flows at Okyereko in the Ayensu basin in the coastal river system of Ghana. In the most extreme case, a streamflow amount of 0.06 m^3/s was equaled or exceeded 99 % of the time at Okyereko.

Groundwater contribution to streamflows in the basin was very low with an estimated baseflow index of 0.14 at Okyereko. This may be attributed to storage materials (soil and aquifer) in the basin having very low permeability.

The study showed that streamflow amount of 0.100 m^3/s would occur at least once every year at Okyereko in the Ayensu basin. Similarly, low streamflows with magnitudes 0.016 m^3/s, 0.010 m^3/s and 0.009 m^3/s are expected to occur at least once in a 10, 50 and 100-year periods, respectively.

Generally, all the distribution functions under calibration and validation modes fitted very well with the mean daily low streamflows in the basin. However, the Normal and Gumbel distributions produced the best fits with NSE equaled to 99.17% & 99.19%, respectively, at Okyereko.

Low streamflow in the Ayensu basin could be described as Normal or Gumbel distributed and thus had less of a tendency to produce unusually extreme low flow at Okyereko. The probability of occurrence of low extreme flows in the basin is very low. Water abstraction from the basin below 0.20 m^3/s at Okyereko is considered reliable and sustainable in terms of use for water supply for domestic, industrial and agricultural use. However with the water stress/vulnerability index for the basin beyond 2020 estimated to be high there is the need to manage this basin sustainably.

Hydrological assessment is streamflow data dependent and predictions for the future are based on historical data or information. It is therefore essential that adequate resources are set aside for the establishment of reliable monitoring stations to collect both meteorological and hydrological data to enhance scientific research in streamflow studies in the river basins of Ghana. Thus, promoting sustainable water supply for drinking, irrigation, aquaculture and fisheries, mining and manufacturing industries, ecological balance and socio-economic development of the country.

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