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Modelling Flow Duration Curve for Upper Cauvery Basin

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Abstract

Effective planning, design, and management of water resource systems necessitate access to long-term runoff records. One of the fundamental approaches in hydrological modeling is establishing a rainfall-runoff relationship, which can range from simple to sophisticated models. These models serve as vital tools in various aspects of water resource development, including resource assessment and the evaluation of anthropogenic impacts such as land-use changes, deforestation, and the construction of hydraulic structures.

This study focuses on modeling Flow Duration Curves and determining the probability of exceedance and percentage of reliable flows for selected catchments. Streamflow data from Kudige, K. M. Vadi, and Akkihebbal catchments in the Upper Cauvery Basin, Karnataka, India, were analyzed. The model's performance was assessed using statistical indicators. At Kudige, a high coefficient of determination (0.995), Nash-Sutcliffe efficiency (0.994), and Kling-Gupta efficiency (0.981) indicated strong model performance. For the other two catchments, results were moderately satisfactory, suggesting variability in hydrological behavior across the basin.

Categories: Environmental Engineering and Sustainability, Water Resources Engineering
Keywords: flow duration curve, exceedance of probability, streamflow modeling, reliable flow, performances

Introduction

Hydrologic modeling of streamflow is essential for understanding and managing water resource systems. It enables comprehensive evaluation across various modeling approaches-ranging from lumped and semi-lumped to semi-distributed and fully distributed models. The runoff or stream flow modeling for a catchment is very sensitive, and it consists of numerous contributing parameters. It demands a diverse set of data sources, including ground-based observations and remotely sensed datasets, to effectively capture the hydrological dynamics. Distributed models are known for their ability to represent spatial variability in catchment responses to hydrological inputs. These models, especially when physically based, are particularly useful in forecasting runoff under wet conditions [1]. However, one of the major challenges lies in the calibration and parameter estimation required for distributed models, which is often time-intensive and computationally demanding. The prediction of ungauged or partially gauged basins has drawn the attention of the hydrologists in the past few years, due to a drastic change in the trends of precipitation and streamflow. To address this, several regionalization [2,3] and non-parametric modeling [4] approaches have emerged. Methods such as the nearest neighbor technique, linear regression, stochastic modeling, and physically based numerical models have been widely employed for streamflow prediction.

Among these approaches, the Flow Duration Curve (FDC) stands out as a robust and widely accepted tool for hydrologic analysis [5,6] particularly in water resource planning and management [7]. FDCs graphically represent the variability and reliability of streamflow, making them valuable for assessing water availability, drought frequency, and flood potential. Land-use and land-cover changes have significantly altered streamflow patterns, often intensifying hydrological extremes like droughts and floods [8,9]. Geographical and physiographic characteristics of a catchment-such as slope, soil type, vegetation, and drainage density-play a pivotal role in influencing its hydrologic response [10]. These flow characteristics [8] help define the catchment's behavior under different hydrometeorological conditions [11,12], thereby guiding the development of accurate flow models. The integration of onsite data with mathematical models may provide better results than traditional models [13]. The statistical tests determine the performance of any prediction models [14]. So far, not much work has been carried out for the partially gauged Upper Cauvery Basin. The modeling of FDC helps in determining reliable flow for future planning of irrigation and water distribution, which is essential.

So in the current study, daily FDC models were developed for three sub-catchments-Kudige, K. M. Vadi, and Akkihebbal-in the Upper Cauvery Basin, Karnataka, India. The probability of exceedance was employed to derive model coefficients, and the modeled streamflows were then evaluated against observed data. Statistical performance metrics were applied to assess the accuracy and reliability of the developed models.

Case Presentation

This study focuses on modeling streamflow using FDCs for three sub-catchments-Kudige, K. M. Vadi, and Akkihebbal-located in the Upper Cauvery Basin, Karnataka, India.

Upper Cauvery Basin, India

The Cauvery river originates in the mountainous Western Ghats region. The basin up to Mettur has an area of 35,145.4 km^2, with many tributaries including the Shimsha, Hemavati, Arkavati, Lakshmana Tirtha, and Kabini. The south-west monsoon covers most of the annual precipitation. Over the basin, the highest rainfall during the south-west monsoon was received along the western border of the basin.

To observe climatic variables, the Indian Meteorological Department and Karnataka Irrigation Investigation Division have established climatic stations and rain gauge stations in and around the basin. To observe streamflow, Central Water Commission has established 12 river gauge sites in upper Cauvery Basin (Figure *1*). The volume of water utilization, the area irrigated, and districts benefited under some of the completed major and medium projects in the upper Cauvery river basin are located in Karnataka state. Major water resource structures in the region include the KRS Dam, Harangi Dam, Hemavathi Dam, and Kabini Dam, which play crucial roles in irrigation, hydropower, and urban water supply. The topography map of the river basin has been represented in Figure *1*. The three sub-catchments along the tributaries (Akihebbal, K. M. Vadi, and Kudige) were considered in the present study (Figure *1*) to model the streamflow through FDC. The details of the three sub-catchments are provided in Table *1*.

Catchment	Kudige	K. M. Vadi	Akkihebbal
Longitude *	75.96	76.29	76.4
Latitude *	12.5	12.35	12.6
Elevation (m)	809	767	745
Drainage area (km^2)	1934	1330	5236
Average rainfall (mm)	3200	1500	1800
Average evapotranspiration (mm)	935	850	810
Peak flow (m^3/s)	2265	681	1480

TABLE 1: The gauging stations of Upper Cauvery Basin

* in degrees

m in meters

km^2 = square kilometers

mm = millimeter

m^3/s = cubic meter per second

FIGURE 1: Upper Cauvery Basin showing the location of gauging stations

FDC is widely used in hydrology to characterize the variability and reliability of streamflow at a given location. It is used to forecast the peak flood, probability of exceedance, and percentage of reliable flow for the catchments. It is one of the popular and traditional methods adopted to determine the yield from a catchment [3]. It is an important signature of the hydrologic response of the catchment [15] and can also be used in a variety of hydrologic analyses related to design and operation of water use or control structures. The FDC for a catchment provides a graphical and statistical summary of the stream flow variability at a given location, with the shape being determined by rainfall pattern, catchment size, and the physiographic characteristics of the catchment. FDC is a plot of discharge against the percent of time the flow is equaled or exceeded. The construction of a FDC using the streamflow observations can be performed through non-parametric plotting position formulae method. The method consisting of the following steps:

(a) The observed streamflow are ranked to produce a set of ordered streamflow from the largest to the smallest observations, respectively;

(b) Each ordered streamflow is then plotted against its corresponding duration.

(c) The percentage probability of the flow magnitude being equaled or exceeded is calculated using the formula $P_e = [\frac{m}{(N+1)}] \times 100$ --------(1)

Where, m = rank given to the ordered streamflow

N = sample length or total number of streamflow

P_e = percentage probability of the flow magnitude being equaled or exceeded

(d) The plot of discharge (Q) and P_e is FDC

Streamflow were subject to frequency analysis to obtain flow quantiles at 1% duration intervals in the range 0%-100%. Derived flow quantiles were used to fit an equation of the following form to obtain the FDC. The exponential fit for the curve was carried and the trend of the future flows was determined.

$Q = ae^{-bP^e}$ ------------(2)

a, b are shape parameters of FDC which are related to the catchment characteristics.

Also, two commonly adopted indices which may be derived from the flow quantiles are as follows:

High flow index (HFI) = (Q_{10}/Q_{50})

Low flow index (LFI) = (Q_{90}/Q_{50})

While the HFI is used to characterize the relative magnitudes of peak flow (Q_{10}) with reference to the median flow (Q_{50}), the LFI characterizes relative magnitudes of low flow (Q_{90}) and the median flow.

The FDC for three sub-catchments was carried out, and all the possible fits (linear, polynomial, exponential, log-normal, etc.) for the stations were examined. It was observed that the FDC showed good fit with exponential equation by showing a high coefficient of determination. Even though the log-normal fit was also closed during the fit, during testing the model, the regression fit was not in the acceptable range. So, analysis of the FDC for these three stations (Akkihebbal, K. M. Vadi, and Kudige) was done only through exponential model in the present study. The models were tested through the statistical performances such as coefficient of determination (R^2), mean absolute error (MAE), root mean square error (RMSE) and bias, Nash Sutcliffe efficiency (NSE) and Kling-Gupta Efficiency (KGE). MATLab tool, Origin software, and MS Excel were used for modeling and plotting.

Discussion

FDC was developed for the three sub-catchments Kudige, K. M. Vadi, Akkihebbal of Upper Cauvery Basin, Karnataka, India. It was noted that these three sub-catchments are tributaries to the Cauvery Basin (Figure *1*). The continuous data for Akkihebbal station available was only for 10 years, after which the station was moved to different coordinates after 2010, so only 10 years of hydrological data was used for the analysis (Table *2*). Through the plots (Figure *2*, Figure *3*, and Figure *4*) and also from Table *1*, it was observed that the streamflow through Kudige was higher compared to the other two stations (Akkihebbal and K. M. Vadi). Later the mathematical models were developed and compared; among them, the exponential model was found to be efficient, and was also able to incur the non-linearity. The selected exponential model coefficients determined have been represented in Table *2*.

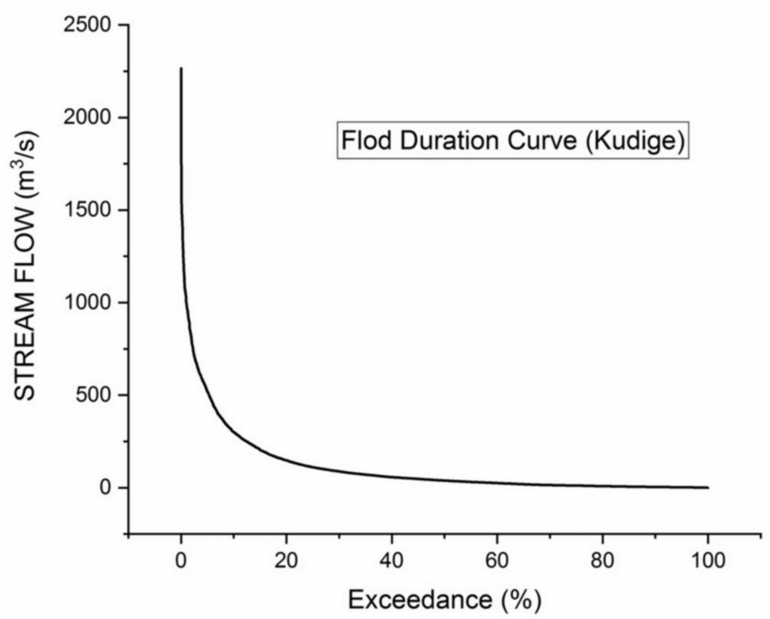

FIGURE 2: FDC of stream gauge station at Kudige

FDC, Flow Duration Curve

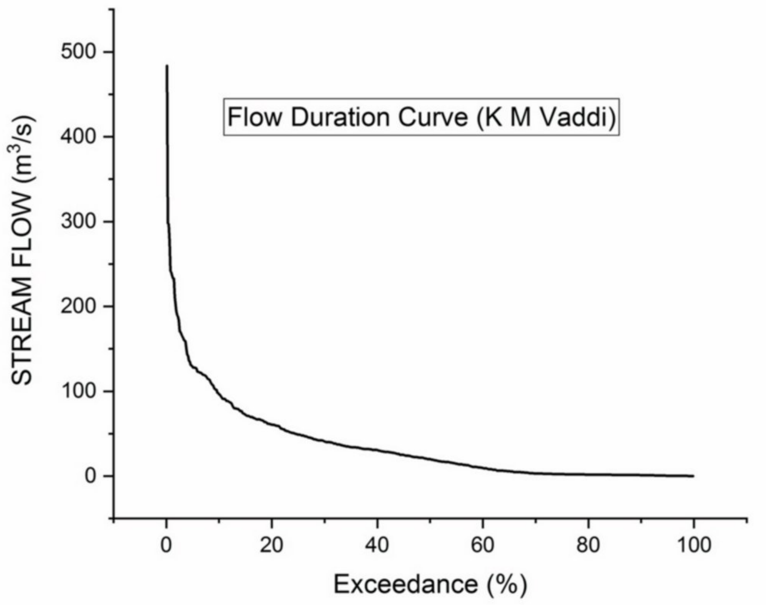

FIGURE 3: FDC of stream gauge station at K. M. Vadi

FDC, Flow Duration Curve

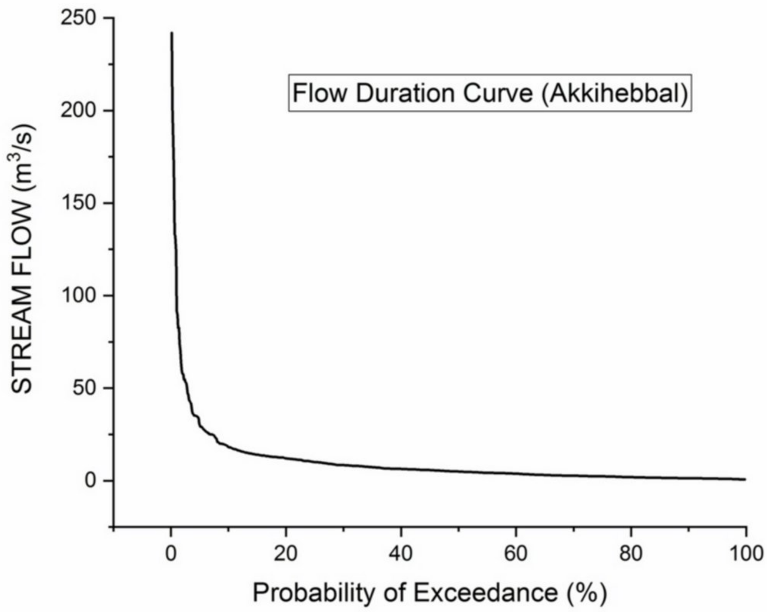

FIGURE 4: FDC of stream gauge station at Akkihebbal

FDC, Flow Duration Curve

Stream Gauge Stations		Akkihebbal	K. M. Vadi	Kudige
Data Considered (year)		200-2010	1980-2010	1974-2011
Coefficients	a	300.43	56.782	433.66
	b	-0.055	-0.02	-0.064

TABLE 2: Coefficients of exponential models fitted for all the sub-basins

From Figure 2, Figure 3, and Figure 4, during modeling of the flow through exceedance probability, it was noticed that the models were not able to determine the peak flows accurately ($Q_{0.1}$ to Q_{10}). Once calibrated and modeled the validation results are shown in Table 3. All the models performed well, which can be observed from the R^2 value. When the models were tested from the observed and modeled flow, the statistical tested value determined was good for Kudige and Akkihebbal stations and, was reasonably well for K. M. Vadi station. But from NSE and KGE, the model was very accurate for Kudige sub-basin and was able to predict very close to the observed values. The residual plots for K. M. Vadi (Figure 5a) showed that the modeled values were lesser than the observed values by falling within the range of -10 to +8 following the bell curve. The regression fit (Figure 5b) was pretty curvy and residual error was more.

Stream Gauge Stations	Akkihebbal	K. M. Vadi	Kudige
Coefficient of Determination (R^2)	0.944	0.755	0.995
Root Mean Square Error (RMSE)	26.479	17.012	3.914
Mean Absolute Error (MAE)	13.209	110.980	2.997
Bias	-12.855	-15.983	-0.598
Nash Sutcliffe Efficiency (NSE)	0.725	0.607	0.994
Kling-Gupta Efficiency (KGE)	0.229	0.183	0.981

TABLE 3: The statistical performances of the model for all the stations

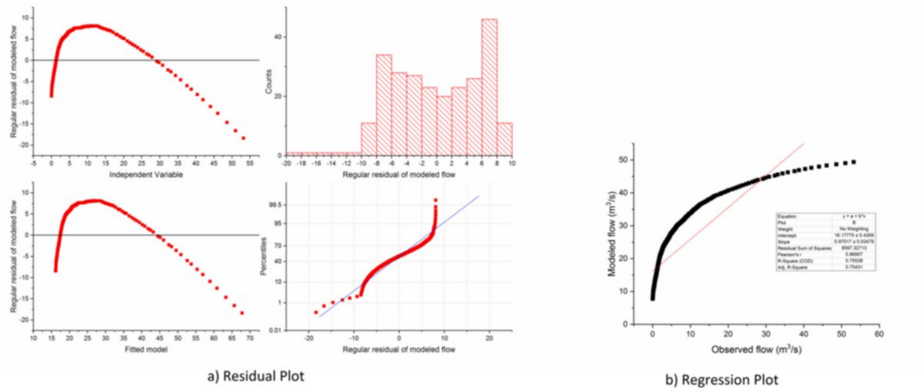

FIGURE 5: The residual and regression plot for K. M. Vadi station

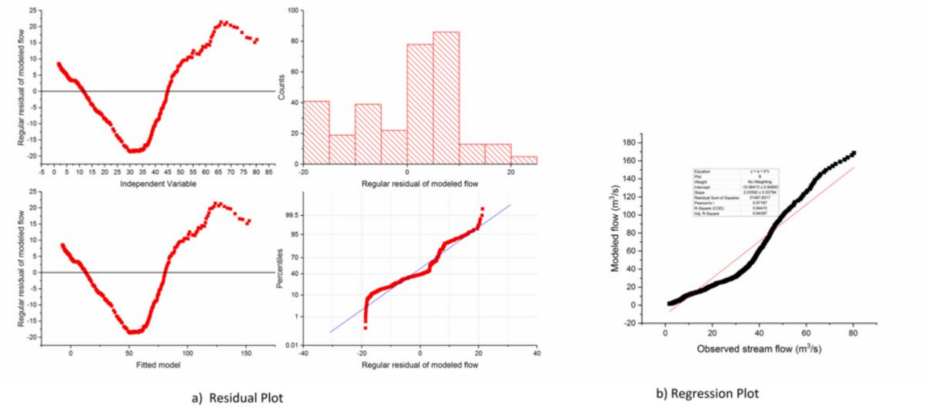

FIGURE 6: The residual (a) and regression (b) plot for Akkihebbal station

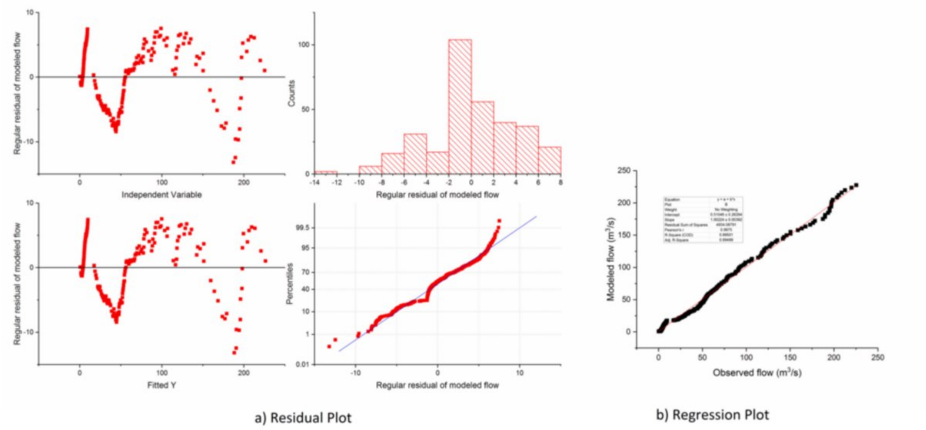

FIGURE 7: The residual (a) and regression (b) plot for Kudige station

The residual plots (Figure *6a*) for Akkihebbal sub-basin showed values ranging from -20 to +20 representing minimal errors. The NSE was comparatively good, but KGE was too low. The regression plot from Figure *6b* follows closer to the regression line, showing minimal errors. Then, through Figure *7a* (the residual plot) and 7b (regression fit) for Kudige, the results showed very good performance with a minimum error difference between observed and modeled flows and good statistical performance.

During testing of the exponential model for all the sub-catchments, it was observed that the peak flows were not determined. But for the streamflow modeled above Q_{10} (10% exceedance probability) was good. The R^2 value (Table *3*) for all the sub-catchment fall within the range of 0.75 to 0.995, which is acceptable for prediction or forecasting globally. The RMSE, MAE, and bias were very minimal for Kudige station compared to other two. For the other two sub-basins, the performance was also well with lower RMSE and MAE. The bias values for Akkihebbal and K. M. Vadi indicate that there is a negative bias i.e. the streamflow predicted are higher than observed. The RMSE determines goodness of fit, which is within a good range of acceptance. The KGE and NSE determines the good hydrological predictions, which were better for Kudige station values, where the residual errors were minimum.

Conclusions

This study demonstrated the utility of FDC modeling for evaluating streamflow behavior in the Upper Cauvery Basin's sub-catchments. The method proved effective in estimating flow variability and reliability using limited observed data, offering a practical solution for hydrological assessments in both gauged and data-scarce regions. The model achieved high accuracy for the Kudige sub-basin, reflecting R^2 of 0.995, NSE of 0.994, and KGE of 0.981. For K. M. Vadi, the respective metrics were R^2 = 0.755, NSE = 0.607, and KGE = 0.183, indicating moderate reliability. Similarly, Akkihebbal showed R^2 = 0.944, NSE = 0.725, and KGE = 0.229, confirming acceptable model performance across physiographic variations.

Quantitatively, the probability of exceedance analysis revealed that the Kudige catchment maintains over

80% of its annual flow volume above the 60% exceedance level, suggesting reliable flow for most of the year. In contrast, K. M. Vadi demonstrated higher variability, with significant drop-offs in low-flow periods, while Akkihebbal provided a balanced flow distribution. Overall, the study confirms that FDC-based modeling is an effective, efficient approach to understanding and managing streamflow dynamics, especially when integrated with statistical performance evaluation.

Water resource planners require quantified information to define the areal and seasonal variations in runoff from partially gauged drainage basins. To predict the flows of the daily and monthly discharges, in this study FDC was modeled and tested with statistical performances and the observation made are listed below.

(i) The model determines a accurate prediction values for Kudige station.

(ii) The flow duration curve can be used to model the streamflows (10% to 90% reliable flows), but not the peak flows.

(iii) FDC determines the response of the catchment and its characteristics.

(iv) It was also observed that there is a declining trend in the flows as the magnitude of the peak was reduced during the later years.

(v) Models for FDC help in planning and management of water resources, and it helps in flood operation and reservoir operations.

Future scope: The future scope must consider the time-bound variation in land-use changes, planning of future demand and also consider uncertainty factors for enhanced predictive capability.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Chandre Gowda C., Kumarraju B. C.

Acquisition, analysis, or interpretation of data: Chandre Gowda C., Kumarraju B. C., Manuvijay H L

Drafting of the manuscript: Chandre Gowda C., Kumarraju B. C., Manuvijay H L

Critical review of the manuscript for important intellectual content: Chandre Gowda C., Kumarraju B. C., Manuvijay H L

Supervision: Chandre Gowda C., Kumarraju B. C., Manuvijay H L

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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