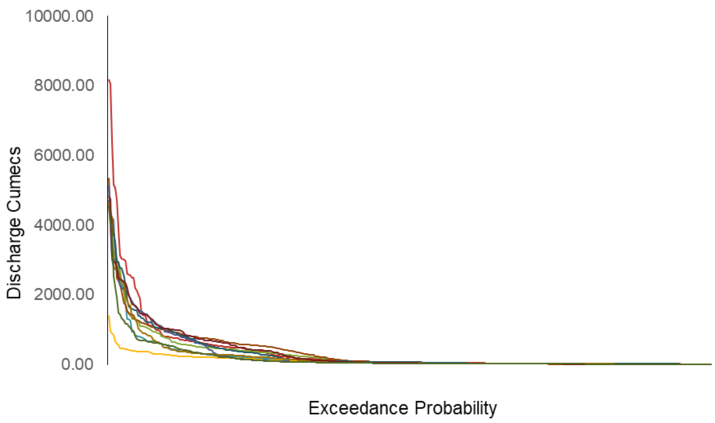
Report No.

ESTIMATION OF CONFIDENCE INTERVALS OF INDEX FLOW DURATION CURVES

FINAL REPORT



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ABSTRACT

A flow duration curve (FDC) provides an estimate of the percentage of time a given streamflow was equalled or exceeded over a period of time. An FDC is the complement of the cumulative distribution function (cdf) of daily streamflow and their interpretation depends on the particular period of records on which they are based. However, if one considers N individual FDCs, each corresponding to one of the individual N years of record, then one may treat those N annual FDCs in the same way as one treats a series of annual maximum and annual minimum stream flows. This annual based interpretation enables confidence intervals and recurrence intervals to be associated with FDCs in a nonparametric framework.

A nonparametric framework based on annual flow duration curve (AFDC) and index flow duration curve is being used for estimation of the confidence intervals (CIs) of AFDCs. Daily discharge (and water level) data for several gauging sites in the lower Godavari basin has been collected from field organizations and related reports published by CWC. Sites having sufficient length of records (around 50 years) has been selected to demonstrate the methodology. The annual discharge data has been plotted to construct AFDCs.

The index flow duration (mean and median) curves are constructed based on median (or mean) flow corresponds to each order statistics. As index duration curves is based on median values corresponds to probability of exceedance 0.50, it also represents the flow duration curves corresponds to return period 2 years (T=1/p). The confidence interval (90%) (lower and upper bounds) of the index duration curve are estimated for two gauging sited in the lower Godavari basin. Based on the distribution of flow values corresponds to each order statistics and plotting positions (Weibull), flow duration curves for different return period are estimated for both the gauging stations. The results of the study can be used to estimate the uncertainty in the availability of flow and also the return period corresponds to various flow duration curves.

INTRODUCTION

1.1 Flow Duration Curves (FDCs)

A Flow Duration Curve (FDC) is a graphical representation that illustrates the percentage of time during which a specific flow in a river or stream is equalled or exceeded over a given period. By arranging flow values in descending order and plotting them against their corresponding exceedance probabilities, an FDC provides valuable insights into the variability of streamflow and the frequency of different flow magnitudes. This statistical tool is widely used in hydrology to analyse the hydrological regime of rivers, assess water availability, and support decision-making in water resource management (Vogel & Fennessey, 1994; Castellarin et al., 2004).

When analysed over multiple years, the Annual Flow Duration Curve (AFDC) provides a summary of the flow characteristics on an annual basis, offering a more comprehensive perspective on interannual variability. The AFDC is critical for understanding the distribution of flow across seasons, which is essential for hydropower, irrigation, environmental flow requirements, and flood risk assessment (Smakhtin, 2001; McMahon et al., 2007).

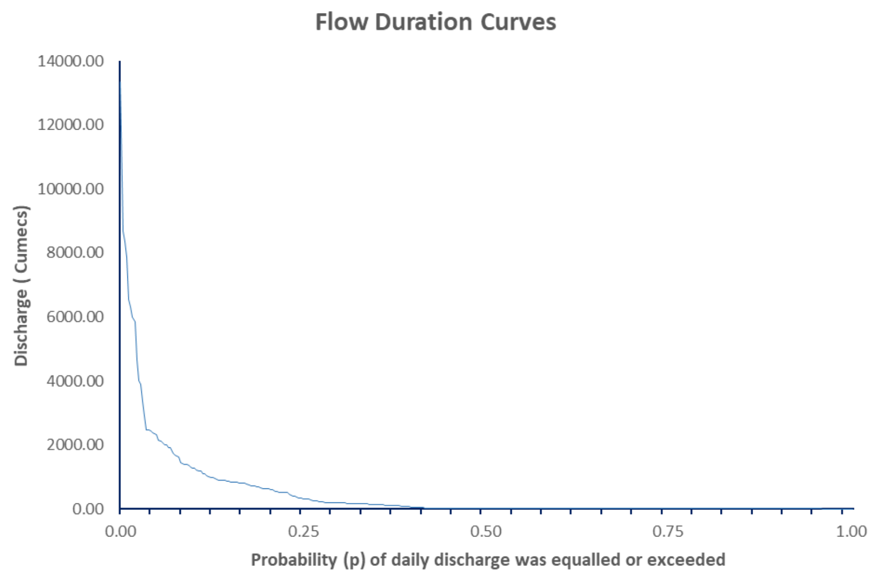

Figure 1.1: Annual Flow Duration Curve (FDC)

Fig.1.1 displaying flow versus exceedance probability for an annual flow duration curve. High flows occur less frequently, while low flows are exceeded for most of the time.

1.2 Historical Development and Applications

The concept of flow duration curves dates back to the early 20th century, when hydrologists began using probability-based flow analysis to assess river behaviour. Foster (1934) first introduced the idea of duration curves as a tool for flow analysis, which was later expanded upon by Leopold et al. (1964), emphasizing its application in fluvial geomorphology and water resources planning.

The application of FDCs has evolved from simple empirical tools to sophisticated modelling techniques integrated with Geographic Information Systems (GIS), remote sensing data, and machine learning algorithms. Early methods relied on manual plotting of observed flow data, but with the advancement of computational power and hydrological models, AFDCs are now generated with high precision using large datasets over extended periods (Castellarin et al., 2013; Stedinger et al., 1993).

1.3 Application of Annual Flow Duration Curves (AFDC) in Hydrology

Annual Flow Duration Curves play a pivotal role in hydrology by helping water managers and engineers assess the long-term variability of river discharge. They are particularly valuable for:

Water Supply and Allocation: Understanding the variability of flow helps optimize water distribution for domestic, agricultural, and industrial use (Vogel et al., 2007).

Hydropower Generation: By identifying low and high-flow periods, AFDCs assist in designing and managing hydropower facilities to maximize energy generation while ensuring ecological balance (Saleh et al., 2016).

Flood and Drought Risk Assessment: Analysing extreme high and low flows through AFDCs aids in assessing flood magnitudes and drought conditions, improving resilience and adaptation planning (Jain & Das, 2010).

Environmental Flow Management: Maintaining minimum flow requirements to sustain aquatic ecosystems and ensure biodiversity is supported by understanding flow frequency and magnitude (Poff et al., 1997).

1.4 Objective and Scope of the Report

The primary objective of this report is to provide a comprehensive understanding of Annual Flow Duration Curves (AFDCs), their construction, and applications in various hydrological domains. The report delves into the methodologies used for generating

AFDCs, explores their applications in water resources management, and presents case studies demonstrating their practical utility. Specific objectives include:

- To outline the theoretical foundation of FDCs and their annual variants.
- To describe the data collection and preprocessing techniques necessary for AFDC generation.
- To explore the methodologies involved in constructing and interpreting AFDCs.

This report aims to serve as a valuable resource for hydrologists, water managers, policymakers, and researchers seeking to enhance their understanding and application of Annual Flow Duration Curves in hydrology.

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2. Theoretical Background

2.1 Fundamentals of Flow Duration Curves (FDCs)

A Flow Duration Curve (FDC) is a probability-based graphical representation that shows the relationship between the magnitude and frequency of streamflow at a specific location over a given period. The x-axis typically represents the exceedance probability (%) or percent of time flow is equaled or exceeded, while the y-axis displays the flow magnitude (m^3/s or cfs) on a linear or logarithmic scale.

A nonparametric framework based on annual flow duration curve (AFDC) and index flow duration curve is being used for estimation of the confidence intervals (CIs) of AFDCs. Considering that the quantile xp are values of a variables X(discharge) having exceedance probability P then FDC can be described simply as a plot of x_p verses P, where P can be computed as complement of the distribution function F of X such that

$$P = 1 - F(X \leq x_p)$$

To estimate index flow duration curve and CIs, the FDC are developed on annual base by considering N annual FDCs, each corresponding to one of the N years of the data. For daily data each curve is a sequence of n=365 values X_i with i=1…n arranged in ascending order $X1{:}n \leq X_{2:n} \ldots X_{n:n}$, where $X_{i:n}$ is the ith order statistics.

AFDCs summarizes the distribution functions of the n order statistics $X_{i:n}$ from annual minima $X_{1:n}$ to annual maxima $X_{n:n}$. Considering the average of the N values available for each $X_{i:n}$, a average AFDC, which represent a typical year wherein the interpretation is not affected by abnormal observations during the period of records. Moreover, other percentile as well as the average can be taken into account to provide α percentile of AFDCs which can be used for estimating CIs for the average.

The concept of FDCs is rooted in hydrology and statistical analysis, where the flow values are arranged in descending order to capture the full range of streamflow conditions—from high flows during wet periods to low flows during droughts. Mathematically, the exceedance probability P_i for a given flow value Q_i where

$P_i = m/(n+1)$

m = Rank of the flow value (starting from 1 for the highest flow)

n = Total number of flow observations in the dataset

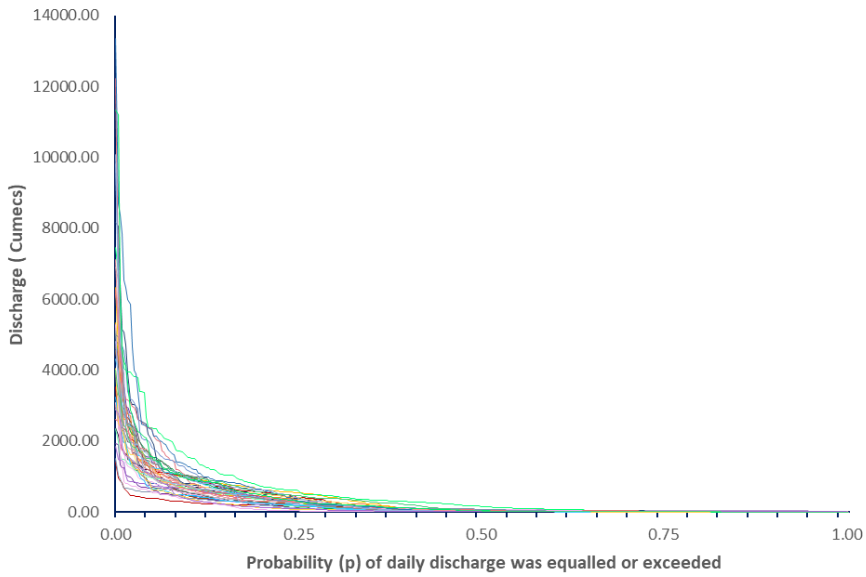

Figure 2.1: Annual Flow Duration Curves (FDC)

Fig. 2.1: A typical Flow Duration Curve (FDC) with flow magnitude plotted against exceedance probability. High flows are equalled or exceeded less frequently, while low flows occur most of the time.

2.2 Types of Flow Duration Curves

Flow Duration Curves can be classified into different types depending on the timescale and purpose. The following annual flow duration curves based on their time scale and purpose are explained.

Annual Flow Duration Curve (AFDC):

Analyzes flow characteristics over an entire year, providing a snapshot of interannual variability. AFDCs are widely used in hydropower potential estimation, water supply planning, and climate change impact analysis (Vogel & Fennessey, 1994).

Daily Flow Duration Curve (DFDC):

Represents flow variability on a daily timescale, useful for examining short-term flow variations.

Monthly Flow Duration Curve (MFDC):

Aggregates flow data on a monthly basis to assess seasonal variations in flow regimes (Castellarin et al., 2004).

Partial Duration Curve (PDC):

Focuses on either high or low flows, typically used for flood frequency analysis or drought studies (McMahon et al., 2007).

2.3 **Annual Flow Duration Curve (AFDC): Concept and Construction**

The Annual Flow Duration Curve (AFDC) is constructed by analysing flow data on an annual basis. It provides a visual representation of the probability that different magnitudes of flow will be equalled or exceeded in a given year. The following steps may be followed to construct the AFDC

Data Collection and Preprocessing:

Obtain daily or hourly discharge data from gauging stations or hydrological models.

Remove erroneous or missing data to ensure data consistency.

Flow Ranking and Probability Calculation:

Arrange flow data in descending order for each year.

Compute the exceedance probability for each flow value using the Weibull formula.

$P_i = m/(n+1)$

m = Rank of the flow value (starting from 1 for the highest flow)

n = Total number of flow observations in the dataset

Plot flow magnitude on the y-axis and exceedance probability (%) on the x-axis. Repeat for Multiple Years and Calculate Median AFDC. Construct AFDCs for several years and calculate the median or representative AFDC for long-term flow analysis.

2.4 **Statistical Properties and Interpretation of AFDCs**

AFDCs provide rich statistical insights into river flow behaviour.

High Flow Zone (0–10% exceedance probability), reflects flood events, extreme precipitation, or snowmelt conditions. This zone is useful for flood control, dam spillway design, and floodplain management.

Medium Flow Zone (10–70% exceedance probability), represents typical flow conditions critical for water supply, hydropower operation, and ecological flow assessment.

Low Flow Zone (70–100% exceedance probability), indicates drought conditions or base flow, vital for maintaining ecological integrity and important for ensuring minimum environmental flows and managing drought conditions (Smakhtin, 2001).

2.5 Applications of Annual Flow Duration Curves

Annual Flow Duration Curves are used extensively in various hydrological applications

Hydropower Design:

AFDCs assist in estimating energy potential, turbine efficiency, and hydropower system reliability (Saleh et al., 2016).

Water Resource Planning:

Used to assess the reliability of water supply systems by understanding flow variability over multiple years.

Flood and Drought Management:

AFDCs aid in identifying the likelihood of extreme events, allowing for effective flood and drought mitigation planning (Jain & Das, 2010).

Environmental Flow Assessment:

Ensuring ecological balance by maintaining minimum flows to support aquatic habitats (Poff et al., 1997).

2.6 Limitations and Challenges of AFDCs

While AFDCs offer valuable insights, they also present certain limitations:

Data Quality and Availability: AFDCs rely heavily on long-term flow data. Missing or inconsistent data can introduce uncertainty in the analysis (Castellarin et al., 2013).

Interannual Variability: High variability in annual flow patterns due to climate change and anthropogenic factors may affect the representativeness of AFDCs.

Assumption of Stationarity: Traditional AFDCs assume stationarity, which may not hold in the face of changing climatic conditions (Arnell & Gosling, 2013).

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3. Introduction

The Lower Godavari Basin is a vital sub-region of the Godavari River system, India's second-longest river. The river is spanning parts of Andhra Pradesh and Telangana, and plays a crucial role in irrigation, hydropower generation, drinking water supply, and flood management. It is characterized by a diverse landscape ranging from hilly forested uplands to the fertile deltaic plains. The lower Godavari basin is shown in the figure below:

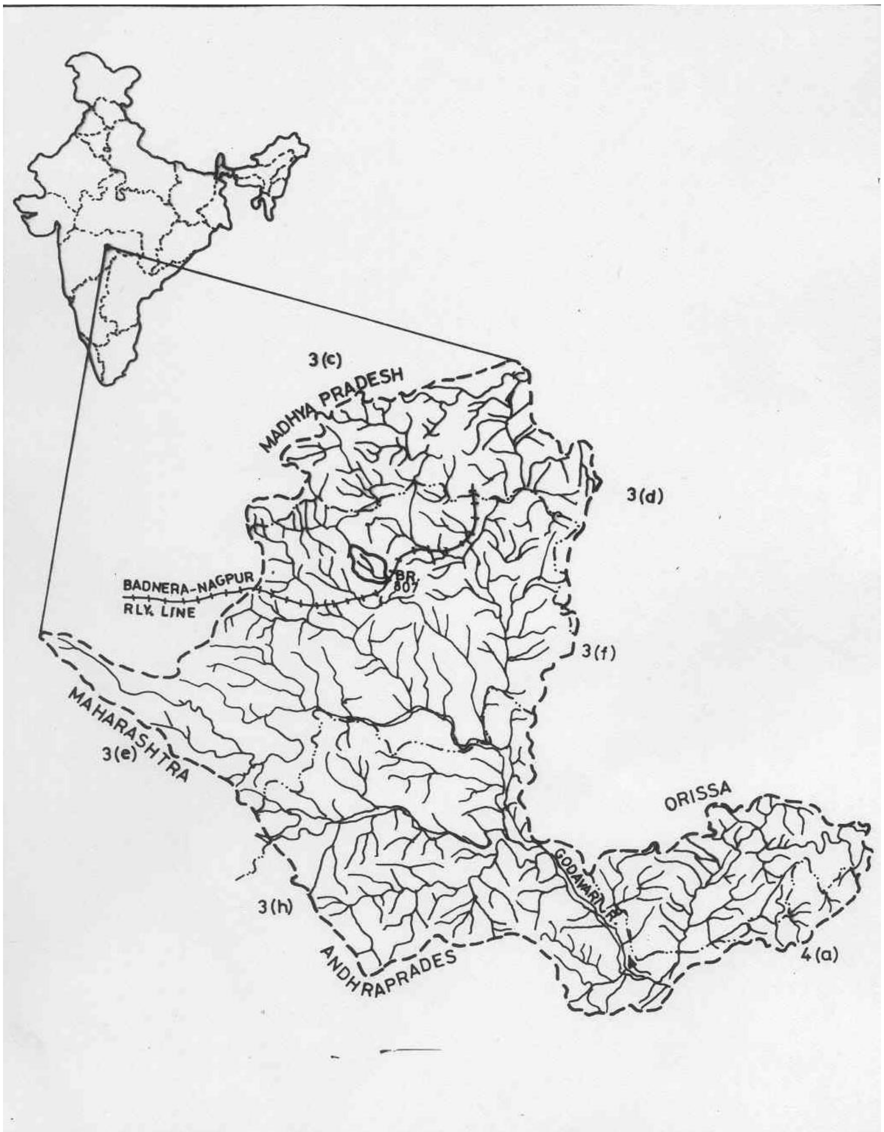

Figure 3.1: Lower Godavari Basin

3.2 Geographic and Climatic Features

The lower Godavri basin extends between coordinates 17°–19° N latitude and 80°–83.4° E longitude. The basin area covers approximately 39,180 km², extending from Bhadrachalam in Telangana to the Godavari delta in Andhra Pradesh. Major towns include Bhadrachalam, Rajahmundry, Dowleswaram, and Amalapuram. The basin has an average annual rainfall between 1000–1400 mm, predominantly during the southwest monsoon (June–September). The Lower Godavari is drained by major tributaries like the Sabari, Indravati, and Pranahita, contributing significantly to the basin's hydrological regime.

3.3 Hydrology and River System

The river has highly seasonal flows with peak discharges during the monsoon. Dry season (January–May) flows are significantly lower. The important gauging sites include Bhadrachalam, Perur, and Dowleswaram for streamflow monitoring. The basin is prone to periodic flooding. The 1986 and 2020 floods were notable, with discharges exceeding 3 million cusecs at Dowleswaram.

3.4 Resource Infrastructure and Projects

The Lower Godavari Basin hosts multiple infrastructure projects designed to harness the river's potential: the following are the details of some important projects:

Polavaram Project

A multipurpose national project aiming to irrigate over 436,000 hectares and transfer 80 TMC of water to the Krishna Basin. It includes a dam, canals, and lift systems, and depends heavily on flow duration curves (FDCs) for dependable water planning.

Hydropower Installations

Projects like Lower Sileru and Sitarama Hydropower utilize basin flows to generate 320–460 MW of electricity, with annual energy yields nearing 1000 million units.

Flood Control Structures

The Dowleswaram Barrage, originally built by Sir Arthur Cotton and modernized in recent decades, regulates flow into the delta and prevents inundation in vulnerable areas like Konaseema.

3.5 Environmental and Socioeconomic Importance

The basin supports extensive paddy cultivation, aquaculture, and drinking water supply for millions of residents. Rich in biodiversity, especially in forested upstream zones and the Godavari estuary. Indigenous communities and rural settlements rely heavily on seasonal flows and groundwater recharge for their livelihood.

3.6 Key Challenges

Flood Risk: Intensifying due to upstream rainfall variability and backwater effects during cyclones. Sedimentation and salinity affect the deltaic zones and reduce reservoir capacity. The climate change influencing monsoon patterns and erratic rainfall and impacting flow availability and project reliability.

4.1 Data Availability

Daily discharge and stage data at Ambabal, Cherribeda, Chindnar, Pollavarm gauging sites in lower Godavari basin has been collected from CWC having long-term hydrological data. The statistical summary of the data is shown in the Appendix-I. A summay of the available gauging sites and the length of data available is shown in the table below:

Table 4.1: Details of gauging sites and available data in the lower Godavari basin

Gauging Site	Data	Period
Ambabal	Gauge-Discharge	1989-2015
Bhadrachalam	Gauge-Discharge	2007-2015
Cherribeda	Gauge-Discharge	1996-2014
Chindnar	Gauge-Discharge	1971-2015
Dowlaiswaram	Gauge-Discharge	1978-2014
Dummugudem	Gauge-Discharge	1978-2014
Jagdalpur	Gauge-Discharge	1964-2015
Kiwaibalenga	Gauge-Discharge	2000-2015
Koida	Gauge-Discharge	1976-2015
Konta	Gauge-Discharge	1964-2015
Kosagumda	Gauge-Discharge	1996-2014
Murthahandi	Gauge-Discharge	1979-2015
Nowrangpur	Gauge-Discharge	,1965-2015
Pathagudem	Gauge-Discharge	1965-2015
Perur	Gauge-Discharge	1965-2015
Polavaram	Gauge-Discharge	1965-2015
Sangam	Gauge-Discharge	1996-2014
Saradaput	Gauge-Discharge	1968-2015
Somanpally	Gauge-Discharge	1964-2014
Tumna	Gauge-Discharge	1989-2015

The Chindnar, Pollavarm has long term annual daily discharge and stage data and selected to demonstrate the methodology. The available data has been pre-processed for any missing data and consistency.

4.2 Analysis and Results

A nonparametric framework based on annual flow duration curve (AFDC) and index flow duration curve is being used for estimation of the confidence intervals (CIs) of AFDCs. Considering that the quantile x_p are values of a variables X(discharge) having exceedance probability P then FDC can be described simply as a plot of x_p verses P, where P can be computed as complement of the distribution function F of X such that

$$P = 1 - F(X \leq xp)$$

To estimate index flow duration curve and CIs, the FDC are developed on annual base by considering N annual FDCs, each corresponding to one of the N years of the data. For daily data each curve is a sequence of n=365 values X_i with i=1…n arranged in ascending order $X_{1:n} \leq X_{2:n} \ldots . X_{n:n}$, where $X_{i:n}$ is the ith order statistics.

Daily discharge (and water level) data for several gauging sites in the lower Godavari basin has been collected from field organizations and related reports published by CWC. Sites having sufficient length of records (around 50 years) has been selected to demonstrate the methodology. The annual discharge data has been plotted to construct AFDCs. Figure 4.1 shows the AFDCs for the period 1971-2013 for the gauging site Chindnar. Figure 4.2 shows the AFDC in the log scale (Y axis). The Figure 1 gives a graphical view of the variability of AFDC over the period of 1971 to 2013 with Figure 4.3 shows the lower and upper boundaries of variation.

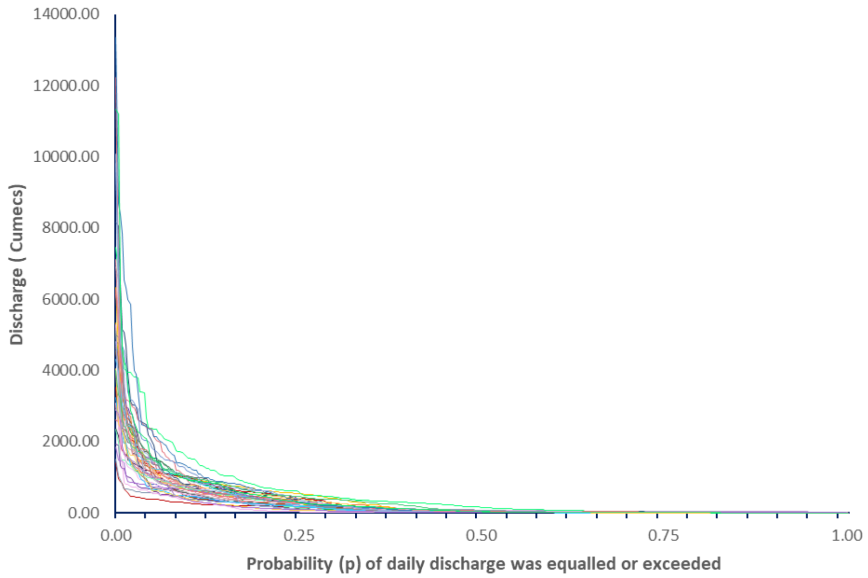

Figure 4.1: Annual Flow Duration Curves for each year for the Chindnar site

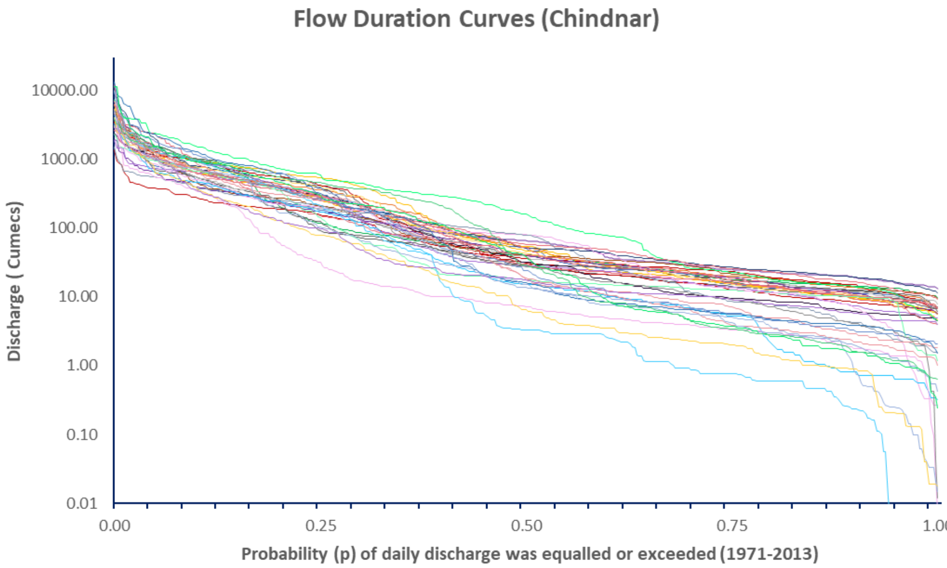

Figure 4.2: Annual Flow Duration Curves for the Chindnar site (log scale)

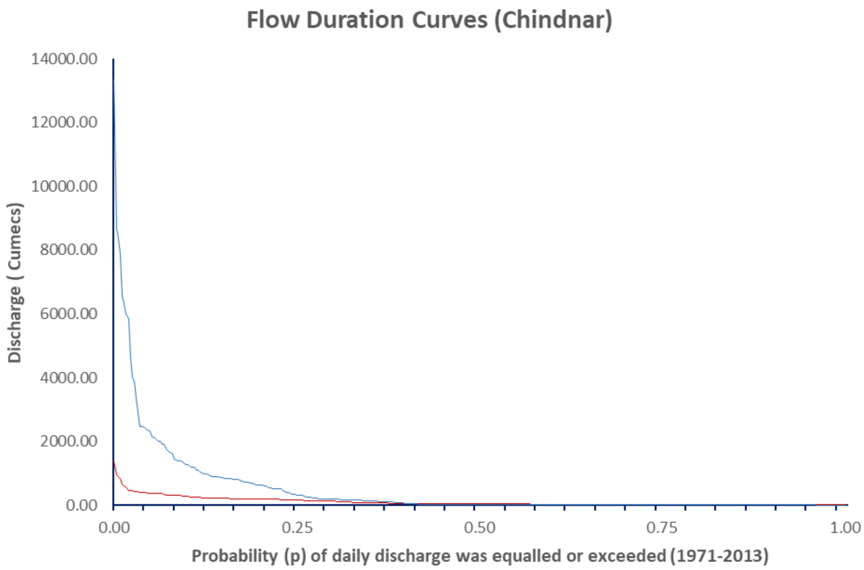

Figure 4.3: Upper and lower boundaries of AFDC for the Chindnar.

The index flow duration (mean and median) curves are constructed based on median (or mean) flow corresponds to each order statistics (Figure 4). As index duration curves is based on median values corresponds to probability of exceedance 0.50, it also represents the flow duration curves corresponds to return period 2 years (T=1/p). Figure 5 shows the confidence interval (90%) (lower and upper bounds) of the index duration curve. Figure 6 shows all AFDC for the period 1971-2013 along with the 90% confidence interval. Based on the distribution of flow values corresponds to each order statistics and plotting positions (Weibull) flow duration curves for different return period are estimated in Figure 7.

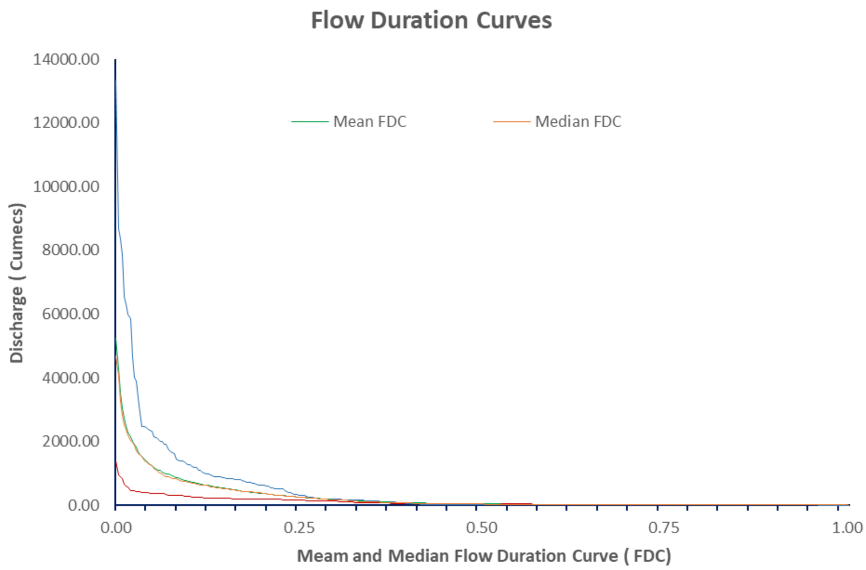

Figure 4.4: Mean and Median AFDC for the Chindnar.

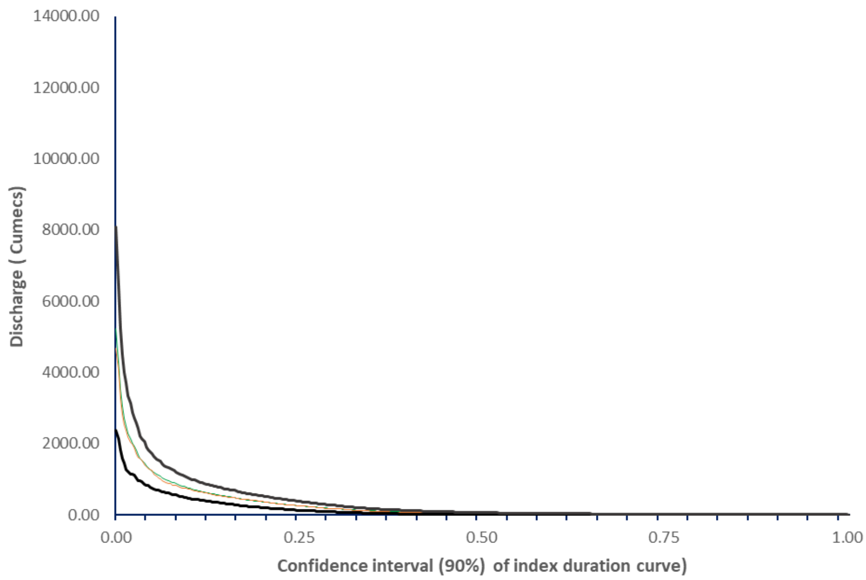

Figure 4.5: Confidence interval (90%) of index flow duration curve for Chindnar.

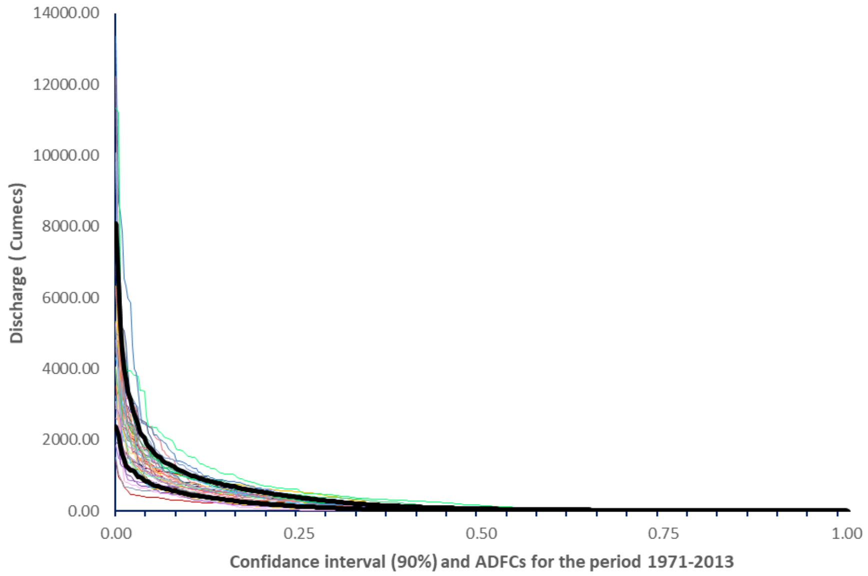

Figure 4.6: Confidence interval (90%) of index flow duration curve for Chindnar.

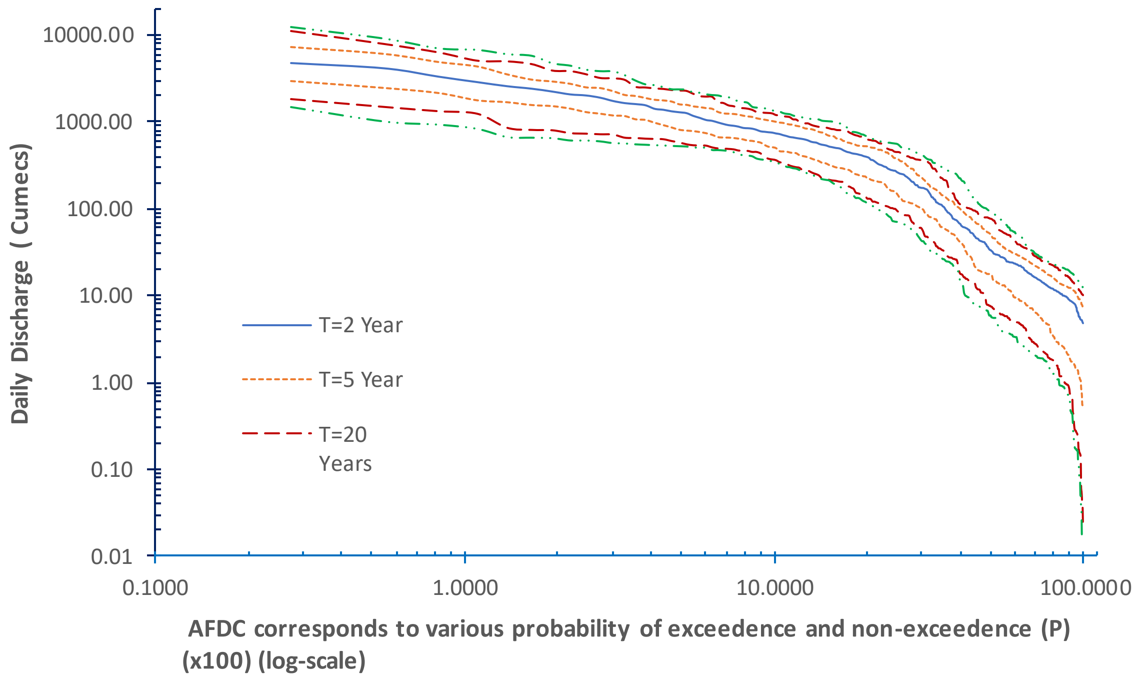

Figure 4.7: ADFC corresponds to various probability of exceedance and non-exceedance (x100) (log scale)

Similar analysis has been also conducted for Polavaram gauging site. The results of the study can be used to estimate the uncertainty in the availability of flow and also the return period corresponds to various flow duration curves. The annual discharge data has been plotted to construct AFDCs. Figure 4.8 shows the AFDCs for the period of record for the gauging site Pollavaram. The Figure 8 gives a graphical view of the variability of AFDC over the period of record with Figure 4.9 shows the lower and upper boundaries of variation.

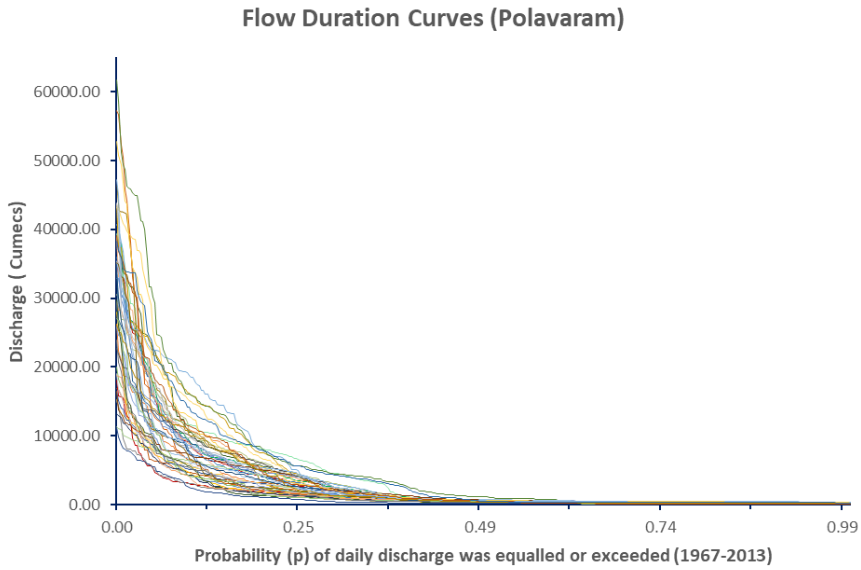

Figure 4.8: Annual Flow Duration Curves for each year for the Pollavaram site

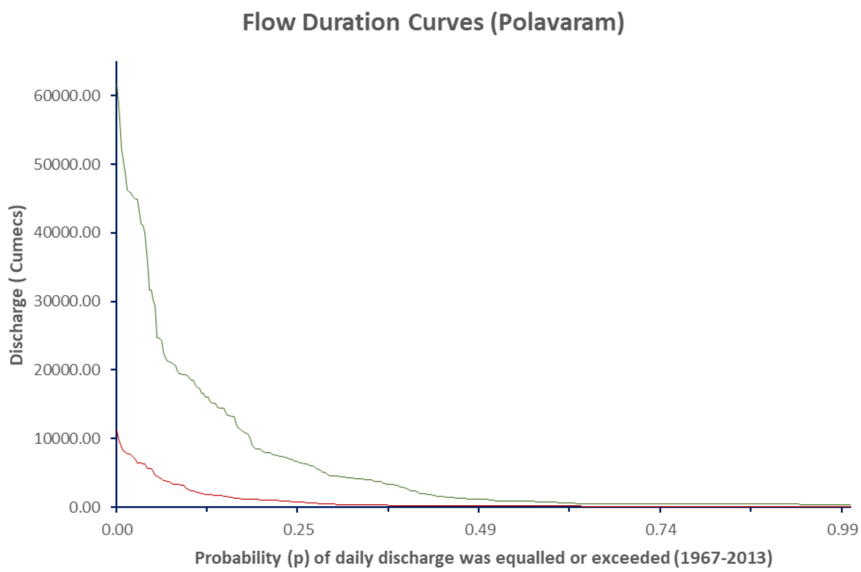

Figure 4.9: Upper and lower boundaries of AFDC for the Pollavaram

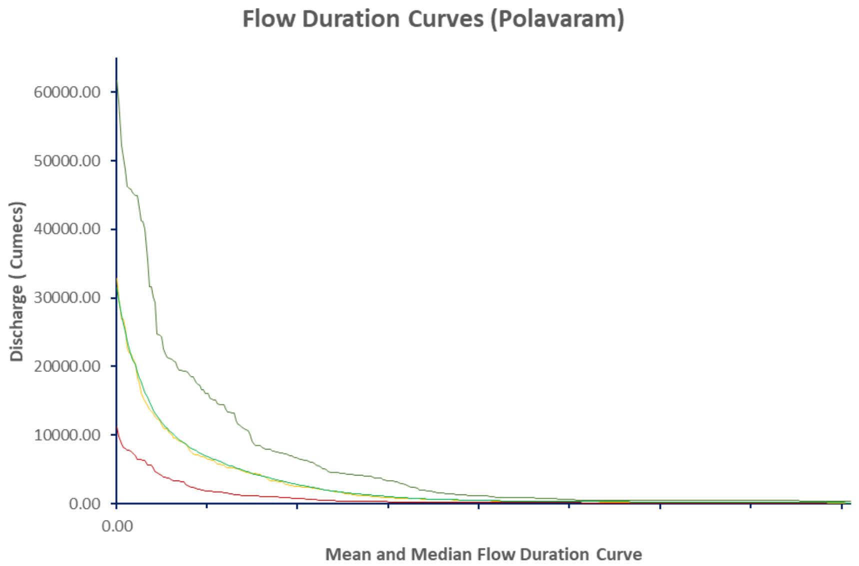

Figure 4.10: Mean and Median AFDC for Pollavarm

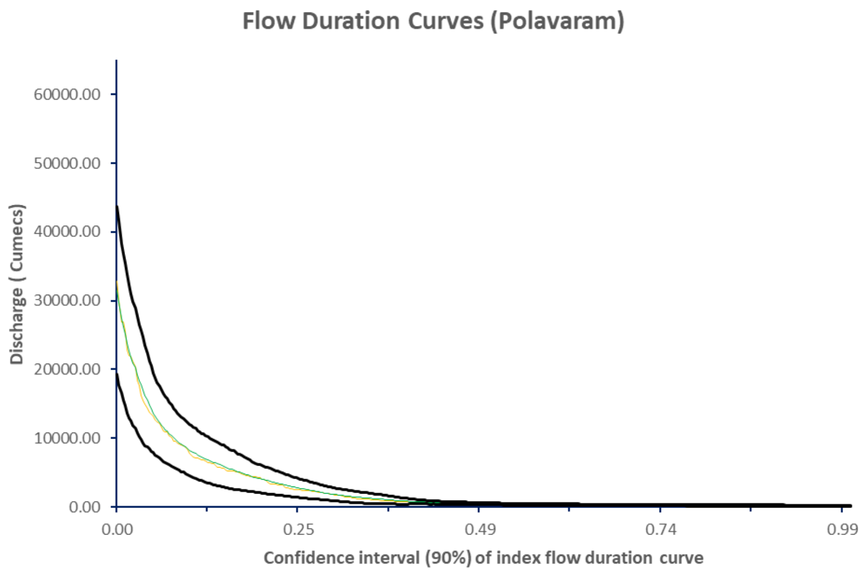

Figure 4.11: Confidence interval (90%) of index flow duration curve for Pollavaram

The index flow duration (mean and median) curve for Pollavaram is constructed based on median (or mean) flow corresponds to each order statistics (Figure 4.10). As index duration curves is based on median values corresponds to probability of exceedance 0.50, it also represents the flow duration curves corresponds to return period 2 years (T=1/p). Figure 4.11 shows the confidence interval (90%) (lower and upper bounds) of the index duration curve. Figure 4.12 shows all AFDC for the period of record along with the 90% confidence interval. Based on the distribution of flow values corresponds to each order statistics and plotting positions (Weibull) flow duration curves for different return period are estimated in Figure 4.13

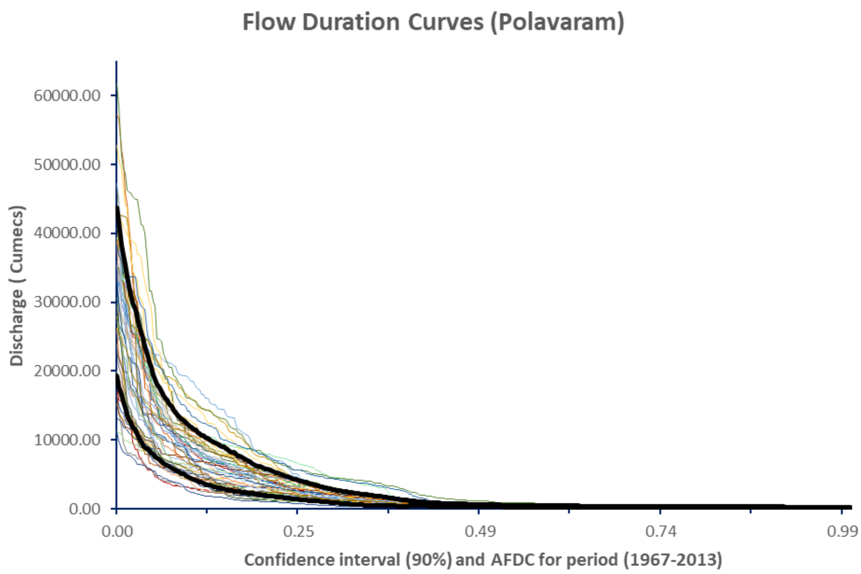

Figure 4.12: Confidence interval (90%) of index flow duration curve for Pollavaram

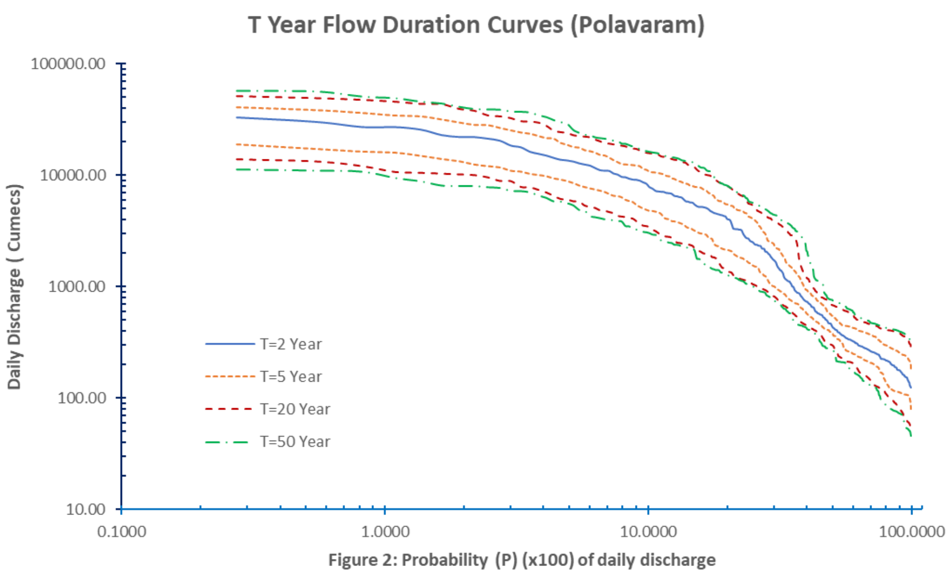

Figure 4.13: ADFC corresponds to various probability of exceedance and non-exceedance (x100) (log scale)

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CHALLENGES AND FUTURE PERSPECTIVES

5.1 Introduction to Challenges and Emerging Perspectives

Annual Flow Duration Curves (AFDCs) are indispensable tools in hydrology, widely used in hydropower management, environmental flow assessment, water allocation, and flood/drought risk analysis. Despite their versatility, several challenges limit their full potential. Advances in technology, data availability, and analytical methods present promising opportunities to address these limitations and improve the applicability of AFDCs in diverse hydrological contexts.

5.2 Key Challenges in AFDC Development and Applications

5.2.1 Data Limitations and Inconsistencies

Accurate development of AFDCs requires high-quality, long-term hydrological records. However, many river basins, especially in developing regions, suffer from limited data availability. Variations in monitoring protocols and equipment calibration also results in data inconsistencies. Instrument failure also causes data gaps in historical records.

Incomplete or unreliable data lead to biased or inaccurate AFDCs, affecting critical decisions in water management. The interpolation of missing data or the use of synthetic datasets introduces uncertainty into the resulting AFDCs (López & Francés, 2013).

5.2.2 Climate Change and Hydrological Variability

Climate change is altering precipitation patterns, snowmelt timing, and river discharge regimes, leading to increased hydrological variability. These variations change frequency and magnitude of low- and high-flow events, more frequent floods and prolonged droughts and uncertainty in seasonal flow patterns.

AFDCs based on historical data may no longer accurately represent future hydrological conditions. As climate-induced variability increases, flow predictions using traditional AFDCs become less reliable, compromising water resource management decisions (Milly et al., 2008).

5.2.3 Limited Incorporation of Human Influences

Human interventions such as dams and reservoirs altering natural flow regimes. Water diversions modify downstream flows. The land use changes alters the watershed hydrology. AFDCs derived from naturalized flow conditions often fail to account for anthropogenic impacts, leading to discrepancies between modelled and observed flow patterns (Graf, 2006).

5.2.4 Scale and Regional Variability

AFDCs are highly sensitive to the scale of analysis and spatial variability of hydrological processes. Applying AFDCs developed for one region to another can lead to erroneous conclusions due to spatial and temporal differences in hydrological behavior (Blöschl et al., 2013).

5.2.5 Uncertainty in Extreme Flow Events

Extreme flow events, both floods and droughts, are inherently difficult to model using traditional AFDCs due to limited historical records of extremes and insufficient data to capture rare events.

5.3 Future Perspectives and Advancements

5.3.1 Improved Data Acquisition and Remote Sensing Techniques

Advancements in remote sensing, satellite hydrology, and sensor technologies are poised to enhance the availability and accuracy of hydrological data.

5.3.2 Integration of Climate Change Projections into AFDCs

Incorporating climate model outputs into AFDC development can account for future hydrological changes.

5.3.3 Incorporation of Human-Induced Modifications

Future AFDCs can integrate the effects of anthropogenic alterations by coupling with reservoir operation models to account for regulated flows.

5.3.4 Application of Machine Learning and AI in AFDC Modelling

Machine learning (ML) and artificial intelligence (AI) techniques offer potential to enhance AFDC accuracy by pattern recognition for Flow anomalies and detection of outliers in flow regimes.

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