A Study on Environmental Flow Requirements in Krishna River Basin

Submitted in partial fulfilment of the requirement for the award of the degree of

Doctor of Philosophy

by

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CERTIFICATE

"This is certify that the thesis entitled A Study on Environmental Flow Requirements in Krishna River Basin being submitted by **Mr. A. Uday Kumar** for award of the degree of Doctor of Philosophy to the Faculty of Engineering and Technology of National Institute of Technology Warangal is a record of bonafide research work carried out by him under my supervision and this thesis has not been submitted elsewhere for award for any degree."

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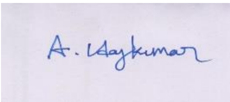
Declaration

"I hereby declare that the matter embodied in this thesis entitled **"A Study on Environmental Flow Requirements in Krishna River Basin"** is based entirely on the results of the investigations and research work carried out by me under the supervision of **Prof. K.V. Jayakumar,** Department of Civil Engineering, National Institute of Technology, Warangal. I declare that this work is original and was not submitted elsewhere for the award of any degree in any other University."



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LIST OF ABBREVIATIONS

1D	One-dimensional
2D	Two-dimensional
ABF	Aquatic Base Flow
BBM	Building Block Methodology
CWC	Central Water Commission
CD	Coefficient of Dispersion
CASIMIR	Computer Aided Simulation Model for Instream Flow Requirements
DEM	Digital Evaluation Model
DRM	Desktop Reserve Model
DRIFT	Downstream Response to Imposed Flow Transformations
ELOHA	Ecological Limits of Hydrologic Alteration
EFM	Ecosystem Functions Model
EFA	Environmental Flow Assessment
EFCs	Environmental Flow Components
EFR	Environmental Flow Requirements
EF	Environmental Flows
EMCs	Environmental Management Classes
EWR	Environmental Water Requirements
EVHA	Evaluation of Habitat Method
EPAM	Expert Panel Assessment Method
FFI	Flood Flow Interval
FDC	Flow Duration Curve
FH	Flow Health
GEFC	Global Environmental Flow Calculator
GIS	Geographic Information System
HAM	Habitat Assessment Method
HSC	Habitat Suitability Curve
HSBC	Hong Kong and Shanghai Banking Corporation
HSI	Habitat Suitability Index
HF	High Flow
HM	Highest Monthly

HA	Hydrologic Alteration
HEC	Hydrologic Engineering Centre
IHA	Indicator of Hydrological Alteration
IFIM	Instream Flow Incremental Methodology
IWRM	Integrated Water Resources Management
LF	Low Flow
LM	Lowest Monthly
MAF	Mean Average Flow
MCM	Million Cubic Meter
NSP	Nagarjuna Sagar Project
NCIWRDP	National Commission on Integrated Water Resources Development Plan
NEP	National Environment Policy
NATHAT	National Hydrologic Assessment Tool
PH	Persistently Higher
PL	Persistently Lower
POF	Percent of Flow
PVL	Persistently Very Low
RVA	Range of Variability Approach
RAP	River Analysis Package
RHYHABSIM	River Hydraulics and Habitat Simulation Program
RAS	River Analysis System
RSS	River System Simulator
RCHARC	Riverine Community Habitat Assessment and Restoration Concept
SPAM	Scientific Panel Assessment Method
SFS	Seasonality Flow Shift
SWaRA	State Water Resources Agency
SWAT	Soil Water Assessment Tool
USFWS	US Fish and Wildlife Service
USFWS	United States Fish and Wildlife Service
WQAA	Water Quality Assessment Authority

Abstract

Rivers play an important role in the transfer and distribution of water resources from the nature to human society. Globally, the utilisation of water quality is increasing with increasing human population with rapidly developing cities, industries, agriculture and power generation which lead to decreasing the freshwater resources availability. This increase is taking place with limited sources of freshwater. In the past two to three decades, hydrological alterations have affected the ecosystem and caused severe changes in the regime of the rivers. Thus, the protection of environmental instream flows to maintain healthy ecosystems has become more and more critical. Environmental Flows (EF) represent the quality, quantity and duration of water flows needed to maintain the species, functions and resilience of freshwater ecosystems and livelihoods of human communities that depend on healthy ecosystems.

Most of the rivers are severely impacted by the anthropogenic activities. Out of the 30 river basins from all over the world that were identified as world-class priorities for the protection of water biodiversity, nine are in India and Krishna River is one among them. Krishna River is located in south India and it is the fourth biggest basin in India. Yet, no studies have been conducted or reported in the literature to assess the impact of anthropogenic activities on this region. Hence, it is necessary to evaluate the potential impact of dams on this watershed, particularly on hydrological alteration, because hydrological alterations cause negative impacts on ecosystem and social aspects. The research consists of analysing flow data at five gauging stations (i.e., DE Sugur, Yadgir, Agraharam, Nagarjuna Sagar Project (NSP) and Vijayawada) under five dams (i.e., Narayanapur, Ujjani, PD Jurala, Srisailam, Nagarjuna Sagar Dam) in Krishna River with long periods of flow data and understanding the hydrological alterations and changes in the ecosystem.

The Indicator of Hydrological Alteration (IHA) software developed by The Nature Conservancy is applied to perform statistical analyses of long sequences of daily observed flows to assess hydrological alteration at the five stations (Richter et al., 1997). For IHA analyses, only normal years which are impacted by the dams are considered. The results of the analysis using IHA explain the changes in the identified 33 parameters, which are reflecting ecological and hydrological changes that occur along the Krishna River due to the

anthropological activities. The study shows that the mean monthly flow in the low flow season in the pre-dam period has a significantly upward trend than in the post-period. The largest positive relative increasing trend was observed in the low flow months, such as February, March, April and May. It is found that minimum extreme flow conditions have been more impacted than the maximum flow conditions. Average low and high flow occurrence shifted forward by 24 and 17 days respectively. The low and high pulse count increased along the basin by 27% and 9%, whereas the count is decreased along basin by 47% and 30% respectively.

Based on the analysis carried out using the IHA tools, it is seen that Krishna River has lost her normal characteristics due to the construction of dams at upstream and downstream of the river. This analysis reveals that EF assessment for the sustainability of the Krishna River is very essential. Environmental Flow Requirements (EFR) for all the stations were calculated using two methods namely Desktop Reverse Model (DRM) and Global Environmental Flow Calculator (GEFC). In DRM method, four classes - A (natural state), B (modified natural state), C (moderate modification) and D (drought condition) were considered to assess EFR. It is observed that the difference between the lowest EFR (lowest percentage of the natural flow) and the highest EFR (highest percentage of the natural flow) in a particular class is slightly lower for the lower class than for the higher class. The results of class B have been taken up for the study in order to manage both the human demands as well as environmental requirements.

The potential environmental flow values for the Krishna River were evaluated by hydrological method called Global Environmental Flow Calculator. GEFC calculates EF values by using seventeen fixed probability distribution points from the natural Flow Duration Curve (FDC). This FDC is generated for six Environmental Management Classes (EMCs) namely, class A, class B, class C, class D, class E, and class F which are ranged from unmodified natural condition to critically modified condition. The ecological management class C was chosen based on the ecological values of the river, and current water resources development projects. Monthly EFR hydrograph for class C was varying from 1.72 m^3/sec to 866.29 m^3/sec for Narayanapur dam, 5.63 m^3/sec to 327.76 m^3/sec for Ujjani dam, 16.8 m^3/sec to 1565 m^3/sec for Srisailam dam, 16.18 m^3/sec to 1412.14 m^3/sec for NSP dam. Non-attainment is used to analyse how environmental flow requirements are different in post-period for two methods (i.e., DRM and GEFC). The calculated EFR under DRM and GEFC method are considered as benchmark values representing the natural flow, and are used to find the flow non-attainment of each month over the post-period. The results of the non-attainment analysis show that the required environmental flows in the Krishna River are not maintained in class B of DRM method and class C of GEFC method with 46.92 % and 43 % of the time in post-period.

Flow Health (FH) methodology was developed by adopting the nine most important ecological indicators. Based on the nine ecological indicators FH score EF regimes are calculated to understand the ecological integrity of the Krishna River. The advantage of FH methodology is that one can see how much alteration can be reduced by considering the calculated EF, while the other two methods, viz., DRM and GEFC are not able to describe about it. For each hydrological station, the overall FH score was determined by calculating the average of nine hydrological indicators. The overall average FH scores of reference (pre-period) and test (post-period) period is 0.84 and 0.59 respectively. These indicate that the Krishna River is highly impacted. FH computes maximum EFR by keeping each indicator score as '1' in the reference period. Two recommendations are assumed in the calculation of EFR, i.e., low risk and moderate risk to environment with required 40% and 30% of Mean Annual Flow (MAF) with respectively of each station. The low-risk regime achieved FH scores of 0.74, 0.73, 0.74, 0.74 and 0.73 with required 40% of MAF of each station. These scores are achieved in the reference period with an average flow rate of 314 m^3/s, 18.4 m^3/s, 337 m^3 /s, 530 m^3/s and 365 m^3/s for Narayanapur, Ujjani, PD Jurala, Srisailam, and Nagarjuna Sagar dams respectively. DRM and GEFC methods are validated with the FH methodology. Total FH score of DRM method for all the dams ranged from 0.60 (Narayanapur) to 0.63 (Ujjani), while the total FH score of GEFC method for all dams ranged between 0.48 (Narayanapur) and 0.50 (Ujjani).

Hydraulic analysis were carried out to determine the acceptable flow regime for aquatic species in the study area. The full range of calculated monthly EF values of three methods are used in determining the physical characteristics of the Krishna River with the reference to the hydraulic analysis. In the absence of detailed information about all the various species and communities in a river ecosystem, fishes are taken as the key indicator species. Habitat Suitability Curves (HSC) were developed for this selected species. The average probable extent of low depth was determined by a GEFC, and the high depth was observed for the FH method. The velocity of the water in the low flow season is very low for the three methods, but the larger water spread area will provide more space for habitation. The water depths of the flow observed in low flow season in the month of March, April and May under Narayanapur, Ujjani and PD Jurala are not satisfactory and not sufficient for habitation. Hence, the minimum flow requirement of the selected fish species was estimated above 15 m^3/s, during the dry season (i.e. March, April and May) of the Krishna River.

The hydraulic analysis is carried out to determine the maximum and minimum water depths and velocity limits for the calculated EFR flow conditions. The Habitat Suitability Index (HSI) was calculated based on the values of water depth and flow velocity under each dam for each method. The three selected approaches are providing excellent habitats under the dams of Srisailam and NSP. Good habitat condition is seen under Narayanapur and Ujjani dams. PD Jurala falls under fair condition under GEFC method. Interestingly DRM method gives higher habitation compared to the FH and GEFC method. This is because the FH method results in higher velocity values which cause a decrease in the habitation, but this type of velocity is good in transporting sedimentation and wastage influences. GEFC is giving low water depth and velocity values.

This study presents the results of the assessment of the changes in the flow regime under the anthropogenic activities for Krishna River, India. From the results, it is observed that the spatial-temporal hydrologic alterations are different among the five stations. It is implied that the overall degree of hydrologic alteration changed at Yadgir and Agraharam station is moderate, and at remaining stations, it is high. Adequate ecological treatments should be made in the middle and lower Krishna River.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Water is the carrier of life that maintains the basic natural needs of all the life activities and ecological processes in nature. Hydrological processes and functioning of a river are extremely important to maintain a healthy aquatic environment and promote well-being of humans through ecosystem services (Acreman and Ferguson, 2010; Poff et al., 2010). Hydrologic processes include surface water storage and hydrodynamic balance processes. Surface water storage processes provide attenuation of high flow events, backwater areas and base flow (Boodoo et al., 2014). High flow is important for aquatic ecosystems as it provides relief from the physical stress. Backwater areas are important to provide low-velocity habitat, and provide refuge areas during high flow periods and increase contact time for biochemical processes. Maintenance of base flow is important for aquatic ecosystems as it helps to sustain longitudinal connectivity in a river and which makes pathways available for organisms to migrate and provides instream habitat during dry periods (Poff et al., 2010). In addition, base flow can maintain soil moisture during dry periods.

The streamflow has been identified as a master variable that controls the physical and ecological processes of the rivers. Ecological processes include activities such as nutrient cycling, movement of sediment and water. These processes interact within a system to form unique ecological characteristics such as stream morphology, stream temperature, composition of biological communities and sedimentation. So, it is imperative to protect ecological functions because biotic communities within a given system rely on the processes and characteristics of flow to carry out different phases of their lives.

The ecological integrity of a riverine ecosystem depends on the natural dynamic character of the streamflow captured by the five components of the flow regime: magnitude, frequency, duration, timing, and rates of change. These five components are dependent on the rise and fall of the water levels. Rise in river water level is favourable to the growth of fishes and helps them to guide the fish swim to spawning, and allow them to feed on the downstream. Natural low water level provides a habitat condition necessary for growth and reproduction of organisms, to promote a healthy ecosystem and maintain necessary ecological processes (Poff et al., 2003). Similarly, many organisms found in the wetlands and floodplains can breed only in high water level conditions. Rivers also play an important role in the transfer and distribution of water resources from the nature to human society. For example, the rich diversity of species in freshwater ecosystems supports economic productivity such as fisheries. They are also a valuable source of genetic information and promote cleaning of water (Dudgeon et al., 2006). Biologically complex and functionally intact freshwater ecosystems provide essential goods and services like food supply, purification of industrial and human wastes, flood control. Biological activities also help in increasing the capacity of ecosystem to adapt to any future environmental alterations like climate change (Peres and Cancelliere, 2016, Pfeiffer and Ionita, 2017). Hundreds of religious and cultural events are regularly organised on the bank of rivers. All these benefits are provided by naturally flowing rivers without any costs being incurred, and these benefits are at all times. When the flow of rivers is reduced by storages and diversions and joined by water from polluted streams, many of these benefits are sacrificed.

Globally, the utilisation of water quality is increasing with increasing human population with rapidly developing cities, industries, agriculture and power generation which lead to decreasing the freshwater resources availability. The increasing demand is taking place with limited sources of freshwater. In the 20^{th} century, human population grew fourfold around the world. At the same time, freshwater withdrawl from the ecosystem has increased manifold. Further, at present more than half of the world's accessible surface water is utilised by the humans, and by 2025 it is estimated that it may increased to as high as 70%. Many of the rivers across the world are changing their flow regimes with respect to magnitude of flow, duration, timing, and frequency. The change in the flow regime is the most dangerous and sustained threat to the ecological stability of the rivers and their associated flood wetlands. The main attribute to this impact is the construction of a large number of barriers, dams and diversion weirs along the rivers and over exploitation of groundwater for the primary uses of domestic water supply, irrigation, industry, hydropower generation, etc. In providing water for humans needs, the water needs of freshwater for species and ecosystems are getting neglected. So,understanding the characteristics of the changes in the flow regime and the analysis of the reasons for these changes are important. This will help to identify the ecological potential of the flow regimes to improve the integrated management of water resources and the protection of the ecosystem along the rivers (Lake, 2003; Boulton, 2003).

In the past sixty years and so, anthropogenic activities have affected the ecosystem and modified it more rapidly and extensively in the river systems than in the previous periods. The flow of the river is regulated by constructing dams which cause changes in physical, chemical and biological characteristics of the riverbed. The regulation of flow is performed on a daily basis and the accumulated water during the rainy season is used to satisfy the water demands during the dry season. Rapid changes in the depth of the water cause water quality changes and harm the aquatic ecosystems along the river. Such activities can lead to loss of habitats, loss of fertility of flooded soil, retention of sediments, blocking of migratory routes, or extinction of native species and the introduction of exotic species (Bunn and Arthington, 2002). If the health of river ecosystems is affected, the entire ecosystem through which water flows also gets affected, including the functioning of water transport corridors. It directly affects the quantity and quality of water resources available for humans. It is found that about 45% of the world's population lives beside river basins under water-stressed condition. In many parts of the world, the eco-products and functions still do not get the attention they deserve, especially in developing countries. So maintaining a minimum flow in rivers is necessary to get the benefits given by rivers. (Nilsson et al., 2005; Poff et al., 2010).

Due to various pressures on water resource in the world, maintaining environmental flow requirement in rivers is important. Environmental flows (EF) provided many benefits to the peoples and nature. Until about 1950s, the focus of water management strategy was almost exclusively on providing sufficient water to meet human needs. This focus began to shift in the 1960s as a global concern for protecting biodiversity and sustaining the environmental systems water resource policy. Initially, the concept of ecological flow was considered to authorise to release minimum water from dams, such as 10% that could be left to the stream, based on percentages of the average annual flow (Tennant, 1976). Later, the percentages of the average monthly flows was used to reproduce seasonal variations (Tharme, 2003). With the advancement in the studies of EF, it is recognised that by maintaining the natural regime or environmental flows in rivers, wetlands, and coastal areas, the ecosystems remain healthy, connected and benefit the people (www.eflownet.org 2012). A global water survey conducted with stakeholders being water specialists, 88% of the water professionals accepted that the environmental flow maintenance is essential to maintain water resources sustainably to meet the long-term needs of people.

1.1.1 Environmental Flows as viewed by different authors

Environment flows have been attracting attention of many researchers and have been defined in various ways and are quoted in this section.

- "Environmental Flow Assessment (EFA) as an assessment of how much of the original flow regime of a river should continue to flow down it and onto its floodplains in order to maintain specified, valued features of the ecosystem" (Tharme, 2003)

- "Environmental flows, can be defined as the water is released and is required in a river system, or let it run for a specific purpose to maintain the natural and functional condition of the ecosystem" (Richter, 2006)

- "According to the statement of Brisbane, environmental flows, including the amount, frequency and quality of water required to sustain freshwater ecosystems, estuaries and human welfare that depend on these ecosystems" (International River Foundation, Brisbane, 2007).

- "Environmental flows represent the quality, quantity and duration of water flows needed to maintain the species, functions and resilience of freshwater ecosystems and livelihoods of human communities that depend on healthy ecosystems" (Poff et al., 2010).

- "Environmental flows as the provision of water for freshwater dependent ecosystems to maintain their integrity, productivity, services and benefits in cases when such ecosystems are subject to flow regulation and competition from multiple water users" (IWMI, 2004)

- "Environmental flows refer to water of a river, wetland or available to maintain ecosystems and the benefits for people coastal area" (www.eflows.org)

1.1.2 Definitions relating to environmental flows

The study of environment flows involve the understanding various terminologies. The most commonly used ones are listed in this section.

Ecological flow: Especially in drought periods ecosystem of river flow restricting the use of water as to preserve the specific characteristics of the river.

Reserve stream: In order to make the amount of water leaving in the river for aquatic ecosystem functions for a long-term service.

Make-up water: As the volume of water released from the dam structure.

Flood flow: Is to remove precipitated solids from rivers with a higher flow momentarily is required.

Streams flow needs: Beginning in the narrower sense, it is often used instead of environmental flows to ensure the survival of fish.

Protection stream flow needs: By protecting the flow in the river, the ecosystem can continue the functioning the reproduction of plants and animals.

1.2 Water Management Issues in India

Variability and seasonality of flows in tropical countries such as India is characterised by a high percentage of annual rainfall (70 % to 85 %) occurring during the South West monsoon season (June/July to September/October). Tropical monsoon hydrology demands development of storage structures and flow diversion schemes on rain-fed and perennial rivers for multipurpose utilisation of water particularly for hydropower generation and irrigation for which high demand exists throughout the year. Himalayan rivers being snow-fed are characterised by perennial flows and steep gradients offering abundant scope for hydropower development. A large number of hydropower schemes in the Himalayan mountainous region spread over parts of India, Nepal, and Bhutan are in different stages of development. A hydropower generation scheme usually consists of a control structure on the river (dam with or without significant storage), a water conveyance system (tunnel, canal) and a power house. The power house, is located at a distance in downstream where topographical head difference between dam location and power house location is utilised for power generation and the water is returned to the river. In several cases, water conveyance system and power house are located underground. A river reach becomes poor of its natural flows due to diversion of flow at control structure. Further, flow in the tributaries within a river reach may get modified due to various construction activities and also if tributary flows are diverted into the conveyance system. Thus, the natural flow regime is altered not only in a river reach downstream of control structure but at several places within a catchment associated with the project layout.

1.3. Justification for the Study

Flow regulations using dams and storage structures affect the ecosystem of the river and biodiversity of the downstream area. In the past decade, hydrological alterations have caused devastating damage to the property and loss of ecosystem across the rivers. Anthropogenic activities are widely recognised to affect flow regimes in many parts of the world (Bradford and Heinonen, 2008). Thus, the losses could be massive in the future due to climate change. Studies related to anthropogenic activates on rivers basin provide information in assessing the Environmental Flow Requirements (EFR). However, the impact of anthropogenic activtes on rivers has not been sufficiently understood at a catchment scale in India, and in particular for Krishna River.

Nationally and internationally, the urgent need to maintain healthy rivers with natural flow regimes is being recognised. The Brisbane Declaration on Environmental Flow (EF) was adopted by more than 750 practitioners from more than 50 countries (http://www.eflownet.org). The announcement included the official pledge to protect and restore the World's rivers and lakes. As of 2015, many countries around the world have adopted EF policies, but their implementation remained as a challenge.

At the river basin scale, EF plays an essential role in the protection of ecosystem. Currently there are tools such as databases, geographic information systems and software for environmental application which can be used together and can be applied as an integral tool to help understand the behaviour of rivers and provide a better perspective on how the flow regime is to be protected to maintain the functionality of the rivers. This study integrates these elements to characterise and determine the rate of natural variation of flow in the Krishna River Basin, with the objective to define the thresholds for ecological flow and enabling to preserve the system. Therefore, the evaluation of hydrological alteration and recommending EFR for the Krishna River will help the policymakers and stakeholders like ecologists for social and economic development planning in the river basin scale.

1.4 Research Gap

An exhaustive review of available literature on environmental flow assessment (Chapter 2 and Chapter 3) shows that:

i. The status of EF research in India may be characterised as being in its infancy because of a very limited knowledge base. EF in India has usually been understood as a flow which is to be released downstream from the dams as a riparian right.

ii. Efforts made by scientists and researchers in different parts of the world on the methods, methodologies, approaches of Environmental Flow Assessments (EFA) vary in terms of use of biotic data and socio-economic aspect of EF. Further, the EF studies and guidelines are region specific.

iii. Water requirement of human, livestock and vegetation in tributaries catchments (terrestrial ecosystem) related with a river reach may be termed as Environmental Flow Requirements (EFR) as these support distinct ecologies. Very limited literature is available on EFR of terrestrial ecosystem. EFR is important as the water requirements of terrestrial ecosystems are currently not explicitly considered.

iv. Usually environmental flows are prescribed in terms of hydrologic indices which may not adequately represent hydraulic habitat requirements of aquatic life.

1.5 Objectives

This thesis aims to understand the effects of anthropogenic activities on the Krishna River to help in the development of an environmental flow strategy. The purpose of this thesis is to systematically investigate the effects of water diversions on riparian vegetation downstream of the diversion points. In achieving this overall objective, the certain specific objectives have been identified. The specific objectives with which the research work has been taken up are to:

i. Determine the changes in flow regime characteristics e.g., timing, duration and magnitude of peak discharge, base flow discharge and duration, and rise and fall rates of the hydrograph.
ii. Identify the post dam hydrologic regime characteristics and compare them to pre-dam conditions to determine whether there is a significant difference by removing climatic impacts.
iii. Reassess the existing methods for computation of Environmental Flow (EF) and evaluate their validity.
iv. Carry out the analysis of the EF using different techniques and their comparison to determine the best method, which can be used in Krishna River and hence suggest the best management practices for maintaining EF of Krishna River.
v. Determine the hydraulic parameters with the help of the calculated EF requirements by using HEC-RAS and ARC-GIS tools.
vi. Develop habitat suitability curves to calculate the suitability index by using hydraulic parameters.

The research consists of analysing flow data at five gauging stations (De Sugur, Yadgir, Agraharam, Nagarjuna Sagar Project (NSP) and Vijayawada) under five dams (Narayanapur, Ujjani, PD Jurala, Srisailam, Nagarjuna Sagar Dam) in Krishna River with long periods of record. Statistical analyses are carried out to the observed daily flows available from the Central Water Commission (CWC) website.

The research addresses the following questions regarding the flows of the Krishna River and their tributaries.

- What are the characteristics of the river flows?
- How has the flow characteristics changed over the past 60 years?
- To what extent the established environmental flow standards can be achieved?

The research also provides a state-of-the-art assessment of modelling and analysis capabilities for addressing these types of questions.

1.6 Significance of Work

Operation of the dams significantly alter the flow regime characteristics when compared to an unregulated time period. Five flow characteristics, namely, the magnitude, duration, timing, frequency and rate of change of flow are examined to understand how the flow regime has changed. The pre dam flow regime conditions and post dam flow regime conditions are examined to determine the five flow characteristics. However, when comparing pre and post construction period flow data, the affected climatic variability flow data were removed. Multiple tools exist in the literature to describe hydrologic characteristics and temporal alteration. In this study, an available tool called Indicator of Hydrologic Alteration (IHA) has been used. IHA generates indicators of hydraulic alteration associated with activities such as dam operations using thirty three metrics that are assessed by comparing measures of central tendency and dispersion between pre-impact and post-impact time frames (Richter et al., 1997).

Efforts made by researchers in different parts of the world on EFA are reviewed to identify the best suitable methods that can be adopted for the Krishna River to determine EFR. The methods used include Desktop Reserve Model (DRM) and Global Environmental Flow Calculator (GEFC). Flow Health (FH) methodology, which was proposed by Gippel et al., (2009) is used in the study by adopting nine most important ecological indicators and the FH scores are calculated by comparing pre-impact and post-impact data. Based on these FH scores of the nine indicators, EFR are estimated. The estimated EF values obtained by these three methods are compared, to determine their effectiveness. Finally, the EF values obtained are compared and validated with the results obtained by the Tennant method which is the most popular and accepted method worldwide.

Hydraulic analysis was adopted to determine the acceptable flow regime for aquatic species in the study area. The values and ranges for the hydraulic parameters are fixed based on the some of the important indicator species found in the Krishna River. For the hydraulic analysis, HEC-RAS model was developed for the Krishna River. The goal of hydraulic model is to determine the maximum and minimum water depth and velocity limits in the basin which are calculated with the help of the quantified EF values. This is done because suitable velocity and depth of the flow in the stream provide maximum food production by keeping much of the food - producing area below the water for aquatic life. Because the stream-bed is considered the most important area for food production, it is usually dependent on the hydraulic parameters. So, the rate at which the hydraulic parameters change with discharge is quite important for defining the hydraulic geometry relationships at a station. The full range of calculated monthly EFR values of three methods are used in determining the physical characteristics of the Krishna River using the hydraulic analysis.

Habitat modelling is used to determine the habitation of the river in terms of velocity and water depth. Based on habitation suitability criteria of selected fishes, Habitat Suitability Curves (HSC) were developed to estimate the habitation in the river. In the habitat modelling process, velocity and water depth values are integrated with the habitat suitability criteria for fishes to get the available habitat as a function of an EF values. Finally, Habitat Suitability Index (HSI) is calculated as a function of EF values and fishes habitat suitability are identified using HSC.

1.7 Contributions from the Study

Hydrologists have used IHA analysis to evaluate the potential hydrological alteration in rivers. This information can provide valuable knowledge for designing infrastructure, reservoir system operational plans, and environmental assessment in Krishna River. Furthermore, Flow Health approach is better suited for environmental flow analysis and to arrive at better and reliable accurate estimates of environmental flow than corresponding Desktop Reserve Model (DRM) and Global Environmental Flow Calculator (GEFC). However, in India many studies used GEFC to assess the EFR at global as well as regional scale while there were no studies which used Flow Health approach. Even the studies carried out using GEFC approach mostly considered only a single dam.

Indicator of hydrological alteration (IHA) is widely used for multivariate analysis for estimating the characteristics of flow impacted by anthropogenic activities. IHA can give a comprehensive understanding in assessment of the hydrological alteration. This approach does not recommend or guide in estimation of EFR. Therefore, it is essential to study the hydrological alteration related with EFR. The main purpose of introducing FH method is to calculate EFR based on the nine most important ecological indicators. The advantage of FH methodology is that the method has the capability to estimate how much alteration can be reduced by considering the calculated EF values, while the other two methods, viz., DRM and GEFC are not able to describe about it.

The surveyed cross-sections and high-resolution DEM along with water depth and velocity hydrograph are used as the input data for the HEC-RAS model to simulate the hydraulic analysis. Furthermore, the habitation modelling approach, is developed by integrating hydraulic analysis data in this study. The water depth and velocity obtained from the hydrodynamic model are used to calculate habitat suitability curve for the study area under the environmental flow context.

1.8 Organisation of the Thesis

After introducing the problem taken up for the study and discussing about the significance of the problem, the objectives of the study are introduced in Chapter 1. A detailed review of the literature related to various methods of hydrological alteration, environmental flow approaches, hydraulic analysis are presented in Chapter 2.

Chapter 3 presents the methodology related to the hydrological alteration, hydrological modelling, and environmental flow assessment methods i.e., Desktop Reverse Model, Global Environmental Flow Calculator, Flow Health methodology and hydraulic analysis. Further, the description of the study area, data needed and available for the study area are also presented in this Chapter.

The impacts of anthropogenic activities on rivers are examined and presented in Chapter 4. Chapter 5 presents the calculation of environmental flow requirements by using two hydrological methods viz., Desktop Reserve Model (DRM), Global Environmental Flow Calculator (GEFC). Besides, non-attainment analysis carried out is also reported in this Chapter.

Chapter 6 presents the Flow Health (FH) analysis. Validation of FH with DRM and GEFC is also done in this Chapter. Chapter 7 describes the hydraulic analysis to quantify the water depth and velocity requirements in combination. Besides, habitation analysis has also been carried out and presented in this Chapter.

Chapter 8 presents the summary of the study, the conclusions arrived, recommendation from the study and suggestions for further research activities. This Chapter also reports the contribution from this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Most of the developmental activities across the world from time immemorial have taken place around the rivers and the water bodies. Many human interventions like construction and provision of storage structures and flow regulators have influenced the natural flow in the rivers, resulting in environmental degradations like loss of biodiversity, fisheries, agricultural productivity, and flora and fauna and the process has been continuing. This necessitates the maintenance of a minimum flow to sustain the environment at or near the pre-developmental stage. Several methods/approaches have been proposed in the literature to study and resolve problems caused due to anthropogenic activities like construction of hydraulics structures, and also for assessment of hydrological alteration and environmental flows. This chapter reviews the various published literatures on hydrological alteration and environmental flow requirements to arrive at a proper methodology to be adopted for the study. The methods range from simple to advance procedures by linking changes in river discharge with geomorphological and ecological response. Recent studies have combined a number of methods to provide comprehensive recommendations on water allocations for ecosystem protection.

2.2 Tools Available to Assess Hydrological Alteration and Environmental Flow

One of the earliest documented literatures mention that the study on instream flow started in Oregon (USA) in 1955, and this program spread across USA and Canada. Studies have been taken up later but the nature of studies varied from place to place depending on the regions' legal requirement, water availability, and characteristics of the aquatic resources. Since then, several works have been carried out but a major amount of works were reported only by the middle of 1970s (Junk et al., 1989). The significance of instream flow studies are influenced by conducting many programmes through the proceedings of conferences, publications and critically evaluating the available methods. Then onwards, the protection and restoration of environmental flows have been drawing more and more attention (Richter et al., 1997).

Numerous tools, methods, and simulation models have been developed to analyse and quantify the degree to which river regimes have been altered and attributed to human activities. Environmental flow analyses methods are developed and modified to protect the five riverine components (hydrology, biology, geomorphology, water quality and connectivity) adequately.

United States Fish and Wildlife Service (USFWS) developed the Instream Flow Incremental Methodology (IFIM), which is a framework for addressing the impacts on river ecosystems due to changes in a river flow regime. The IFIM adhered to the growth principle. If a solution cannot be found out with one attempt, the problem is slightly redefined until a solution can be found. The incremental approach is valuable when applied to the multiple aspects needs like ecological needs, human needs, irrigation needs, fishes needs etc., (Postel and Richter, 2012; Nestler et al., 2018). IFIM has the following major principles:

a. Implementation of an instream flow regime should be a part of water management system.
b. IFIM is designed to estimate the impacts of river in different alternatives.
c. Analytical procedure of IFIM computer model can predict the changes in fish habitat due the flow alterations.
d. IFIM also has a capability to evaluate impacts that happen due to the changes in channel structures and adding waste loads from the pollution sources into the rivers. In some States of the USA, the use of IFIM has become a legal requirement for assessing the impacts of dams or abstractions.

The Riverine Community Habitat Assessment and Restoration Concept (RCHARC) was developed by Peters et al. (1995) by integrating habitat development with the stream restoration process. The RCHARC takes the spatial distribution and many other flow conditions into account and considers the impact of human activities such as damming and channelisation. The RCHARC methodology also has the potential to assess habitat quality.

The US Fish and Wildlife Service also developed the Aquatic Base Flow Method (USFWS ABF). USFWS ABF assumes that the most critical circumstance of a flow regime is required during the month of August. This assumption is made because in the month of August, the metabolic stress to aquatic organisms is high due to the high water temperature, low dissolved oxygen, and low or diminished food supply.

The River Analysis Package (RAP) developed by the Australian Cooperative Research Centre for Catchment Hydrology in 2005 allows the user to define the ecologically relevant statistics for individual work. This function is carried by a tool called Eco Modeller. Eco

Modeller provides all ecological response models, in which user can specify his own choices. This approach is a statistics analysis which combines the time series relevant to ecosystems and water management alternatives. It is extensively used in some river basins in Australia (Hickey et al., 2015).

Hydrologic Engineering Centre (HEC) developed the Ecosystem Functions Model (HEC-EFM) to study the changes in the ecosystem responses in flow regime of a river and connected wetland. HEC-EFM analyses involve statistical analyses of relationships between hydrology and ecology by using Geographic Information Systems (GIS) (Hickey et al., 2015). Through this process, the existing ecologic conditions are studied, promising restoration sites are highlighted, and various alternatives according to predicted ecosystem changes are assessed. HEC-EFM has many strengths, most notably its capability of testing for many ecological relationships and management scenarios, like linking ecology with established hydrologic, hydraulic and GIS tools. It can also be applied quickly and inexpensively, and scientific expertise can be merged into the model (Hickey et al., 2015).

Multivariable approaches, such as the Indicators of Hydrologic Alteration (IHA) were developed by the Nature Conservancy and introduced by Richter et al. (1997). The IHA method is a simple approach requires low cost to process the daily discharge data and to characterise altered and natural hydrologic regimes. The method calculates 33 ecologically parameters and can be used extensively to characterise streamflow alteration (Mathews and Richter, 2007; Anderson et al., 2020; Magilligan and Nislow, 2005; Galat and Lipkin, 2000; Boever et al., 2019; Shiau and Wu, 2004; Yang et al., 2008; Maingi and Marsh, 2002; Zuo and Liang, 2015; Liu et al., 2012; Zhao et al., 2012).

Later, the National Hydrologic Assessment Tool (NATHAT), developed by the United States of Geological Survey (USGS) has expanded over the last few years. The NATHAT is a similar tool like IHA, but it is difficult method to use since it includes a stream classification system along with 171 flow parameters (Henriksen et al., 2008).

2.3 Methods Availability to Assess Environmental Flow Requirements

Different methodologies have been developed and adopted to assess the environmental flow requirements. Available literature identify more than 200 environmental flow methods that are available worldwide. The methods are classified into two: the prescriptive and interactive methodologies (Tharme, 2003). The prescriptive methodology provides a single flow regime to maintain a river condition and is suitable where objectives are clear and conflicts are minimum. The interactive methodology provides a range of flow regimes each linked to different river conditions and is suitable where the users are many. The prescriptive approaches can be subdivided into hydrological index methods, hydraulic rating methods, habitat method, and expert panel method. The interactive approaches, also called as holistic methods, include the Instream Flow Incremental Methodology (IFIM) and Downstream Response to Imposed Flow Transformations (DRIFT) method, which are problem solving tools with the outputs as a set of options or scenarios. The IFIM is a very popular method for stream habitats.

2.3.1 Hydrological methods

Hydrological methods use historical flow records to model hydrologic flow regimes for deriving ecologically relevant flow statistics. If the flow data do not exist, a simulated natural flow regime can be created with a physically based hydrological model by removing anthropogenic disturbance from the modelled conditions. For example, Mittal et al., (2014) simulated the natural flow regime for Kangsabati River in the state of West Bengal in India by using SWAT by removing urban and agricultural development from the land use input layer and converting those lands to forest. Examples of hydrologic methods include the Tennant Method, the Flow Duration Analysis Method, The Range of Variability Approach (RVA), Low flow index and the Percent of Flow (POF) approach (Richter et al., 2011; Tharme, 2003).

From 1958 to 1975, Tennant (1976) systematically collected biological and hydrological data from rivers across the United States, and compared the river biological attributes with their hydrologic conditions. This method was developed from field assessments within the states of Montana, Nebraska and Wyoming and understanding the relationships between discharge and aquatic habitat and sediment movement and recreation. Based on his observations, Tennant proposed some guidelines for protecting the rivers by releasing environmental flows, which became known as the Tennant Method, also known as the Montana method. This method has been the most commonly applied environmental flow assessment method globally. The method relates seven percentages of Mean Annual Flow (MAF) on a seasonal basis to the environmental conditions of the river as shown in Table 2.1 (Tennant, 1976). For example, 200% MAF is considered as an adequate flushing flow, 60% MAF is considered to provide optimal habitat and 10% is considered as ecologically poor or minimum (Tharme, 2003).

Table 2.1 Tennant flow statistics

Condition	Wet Seasons	Dry Seasons
Flushing/maximum flow (from 48-96 hours)	200% Mean Annual Flow (MAF)	N/A
Optimum range of flow	60 - 100% MAF	60 - 100% MAF
Outstanding habitat	60% MAF	40% MAF
Excellent habitat	50% MAF	30% MAF
Good habitat	40% MAF	20% MAF
Fair or degrading habitat	30% MAF	10% MAF
Poor or minimum habitat	10% MAF	10% MAF
Severe degradation	<10% MAF	<10% MAF

According to French freshwater fishing law, flow in a river section must be at least a minimum of 1/40 of the mean flow for existing schemes and 1/10 of the mean flow for new schemes (Souchon and Keith, 2001).

In UK, an index of natural low flow has been employed to define the environmental flow. Q95 (i.e. that flow which is equalled or exceeded for 95% of the time) is often used. However, in other cases, indices of rarer events (such as mean annual minimum flow) have been used. The figure of Q95 was chosen purely on hydrological grounds. However, the implementation of this approach often includes ecological information (Dunbar et al., 2004).

The Flow Duration Curve (FDC) analysis uses various exceedance percentiles on the flow duration curve as flow indices. A FDC displays the percentage of time the discharge is equalled or exceeded. Comparing FDCs between natural and altered river regimes can diagnose changes in streamflow variability quickly and powerfully, and this approach has been used widely as environmental flows guideline (Li et al., 2007). Commonly applied general indices include the discharge that is equalled or exceeded 90% of the time and 7Q10, which is the low flow event that occurs for a duration of seven days with a 10 year return period (Tharme, 2003). While 7Q10 is a commonly applied index, it has been demonstrated that it is not sufficient for protecting aquatic habitats (Richter et al., 2011). Flow indices that make a clearer link between discharge and ecology have been developed for specific sites. For example, flushing flow can be used to remove fine sediment from the channel bed to provide spawning ground for fishes and has been used as a flow index to maintain habitat suitable for spawning. The main weakness of flow duration curve analysis is that it does not provide any information about the timing, duration of specific flow events or rate of change of the flows, which are all recognised as important components of a complete EFA. This problem can be partially avoided by using monthly or seasonal FDCs but this does not solve the problems of sequential duration and rate of change.

Indicator of Hydrological Alteration (IHA) was developed by U.S Natural Conservancy (http://www.nature.org/) to calculate the hydrological changes caused by human activities. IHA uses 33 parameters as indicators of hydrologic alteration. The 33 hydrological parameters are categorised into five groups addressing the magnitude, timing, frequency, duration, and rate of change of flows. Magnitude is a measure of the flow volume associated with a particular hydrologic event; frequency describes how often events occur within a specific time period; duration is how long an event occurred; timing is when the events occur within a specific time period; and rate of change is how rapidly the hydrograph rises and falls. To calculate these 33 IHA parameters, the use of Range of Variability Approach (RVA) is suggested by Richter (1997). RVA includes four steps:

i. Comparing two distinct datasets, such as pre-impact and post-impact flow data.
ii. The flow variation divided into three categories: a) lowest category considered the flow having one standard deviation from the mean which contains all values less than or equal to the 25th percentile; b) the middle category contains all values falling in the range of the 25th to 75th percentiles; and c) the highest category contains all values greater than the 75th percentile.
iii. Calculating the expected frequency that post-impact flows should fall into each RVA range based on data record length and pre-impact frequency.
iv. Finally hydrologic alteration (HA) factor for each of category is calculated by using (Eqn.2.1). Positive HA correspond to increased post-impact frequency and range from values greater than 0 to 1. Negative HA corresponds to reduced post-impact frequency and has a lower limit of in the range of 0 to -1. A value of 0 (zero) indicates that there was no alteration.

$$HA = \frac{\text{Observed Frequency} - \text{Expected Frequency}}{\text{Expected Frequency}} \qquad \text{(Eqn. 2.1)}$$

where,

Observed frequency is the number of years that fall within the targeted range;

Expected frequency is given by number of values that fall in the each category during the pre-impact period multiplied by the ratio of post-impact years to pre-impact years.

HA is equal to zero when both frequencies are equal.

Richter et al. (1997) proposed three-classes for the degrees of Hydrological Alteration as (i) no alteration (0.0–0.33), (ii) moderate alteration (0.34–0.67), and (iii) high alteration (0.68–1.0).

2.3.1.1 Strengths and weaknesses of hydrological methods

The hydrological methods provide simple, rapid, inexpensive, and low resolution assessments that are suitable for reconnaissance level of EFA. These methods can also be used as a component of Holistic Methods (Tharme, 2003). However, these methods are not suitable for high controversy situations where there are multiple stakeholders and where there are important biological values to be protected. Hydrologic methods can be difficult to implement when no data are available to develop a reference regime and difficult to defend if the connection between the flow regime and ecology is not clearly understood (Tharme, 2003). If hydrological models are used, then significant expertise is required to set-up and run the model properly.

2.3.2 Hydraulic methods

Hydraulic methods determine the values of hydraulic variables (such as maximum depth, wetted perimeter, velocity or longitudinal connectivity) at a single or multiple river cross-sections for the maintenance of specific components of aquatic ecosystem health. These methods are directly connected to specific aquatic ecosystem integrity with a particular hydraulic variable, and the maintenance of a given discharge depends on the concept of hydraulic variable and the aquatic ecosystem. The relationship of the hydraulic variable to discharge is usually compared using a breakpoint along the discharge variable graph. For example, the variable wetted perimeter is commonly used as a representation for fish nutrition and benthic invertebrate production within riffle biotopes (Acreman and Ferguson, 2010). It can be noticed from the graph in Fig. 2.1 use the same data but have different breakpoints. Fig. 2.1 thus demonstrates the subjectivity of the breakpoint method. In addition, any evidence to support the assumption that the breakpoint in Fig.2.1 is a threshold for a healthy aquatic ecosystem (Acreman, 2016). Hydraulic modelling software such as HEC-RAS can be used to assist with developing relationships between hydraulic variables and discharge (Tharme, 2003). Alternatively, relationships between discharge and hydraulic variables can be determined empirically using regression equations.

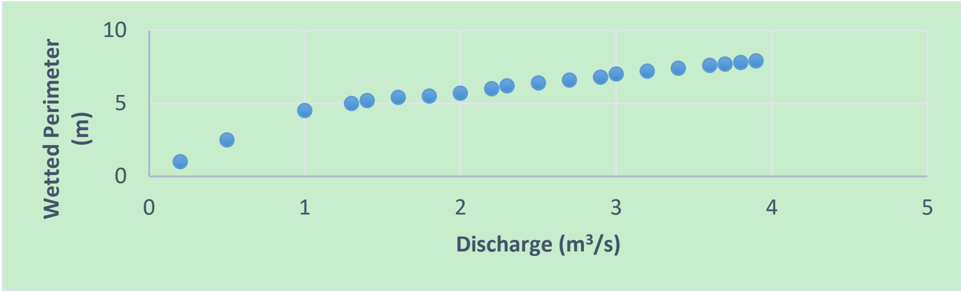


Fig.2.1 Wetted perimeter discharge relationship with the same data but different breakpoints

2.3.3 Strengths and weaknesses of hydraulic methods

The hydraulic methods provide a relatively simple, cost effective method for determining EFR. These methods also provide a more explicit link between discharge and ecology than the hydrological methods by incorporating ecological information related to physical habitat requirements at various discharges. In addition, the hydraulic technique can be expanded to incorporate habitat requirements for several species with a moderate amount of effort and expense. A major weakness of the hydraulic methods is that the health of a given aquatic ecosystem component is dependent on a single hydraulic variable or a small group of hydraulic variables. The results of the hydraulic methods depend only on minimum flows to sustain given habitat variables and do not consider other aspects of a natural flow regime such as timing, duration, rate of change and frequency. Further, it may be difficult to obtain a quality relationship between discharge and the hydraulic parameters of interest which can significantly impact the effectiveness of the selected EFR. Another disadvantage of the hydraulic method is that the hydraulic relationship is limited in spatial resolution to the cross-sections that were investigated and it will be difficult to expand to out of channel ecosystem components such as riparian vegetation.

2.3.4 Habitat simulation methods

The habitat simulation methods are extension of the hydraulic method to determine quantity and suitability for given target species of habitat under various flow conditions (such as depth, average column velocity). King et al., (2000) identified over 25 habitat simulation methods, with Physical Habitat Simulation (PHABSIM) used within the Instream Flow Incremental Methodology (IFIM) being considered as the most advanced. PHABSIM has two main components, a hydraulic simulation component and a habitat simulation component. In this method, simulations are carried out to generate the hydraulic parameters, like depths and velocities at various discharges. Habitat simulation methods use the results of the hydraulic simulation models to link the physical conditions of the target species at various stages of the life history of the species, called Habitat Suitability Criteria (HSC). HSC are calculated for each cell and at each time step of the model as seen typically in Fig. 2.2. Casper et al., (2011) coupled the distributed hydrological model SWAT with PHABSIM for the calculation of EFRs in Hillsborough River, Florida. Other habitat simulation programs, which are both variations of PHABSIM, such as the River Hydraulics and Habitat Simulation Program (RHYHABSIM) and Riverine Community Habitat Assessment and Restoration Concept (RCHARC) are also found in the literature. The Computer Aided Simulation Model for Instream Flow Requirements (CASIMIR) is another software that allows for separate calculation of the effects of hydropower fluctuation on instream habitat (Richter et al., 1997). Other habitat simulation methods include the Evaluation of Habitat Method (EVHA) and the River System Simulator (RSS).

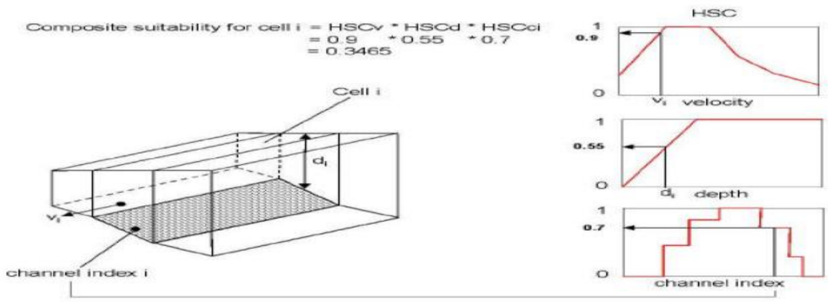


Fig.2.2 Graphic demonstrating the calculation of Habitat Suitability Index (HIS) for cell i Casper et al., (2011)

2.3.5 Strengths and weaknesses of habitat simulation

The main advantage of the habitat simulation methods is that they provide a relatively scientific and a strong EF assessment approach by allowing the assessment of flow for multiple scenarios for various species and life stages. It is a software-based model, with an in-built training module. The model is easy to learn and apply. In addition, habitat simulations can easily be incorporated into holistic methodologies. Habitat simulation models require significant expertise to run the model properly. Explanation of the model output requires understanding of the limitations of the input data and the model structure. These models can also be spatially restricted to the surveyed cross-sections and may be narrow in scope only focussing on particular species of interest. Further, this method does not incorporate broader aspects of the riverine landscape such as geomorphic functions and does not account for long term changes in river morphology. Finally, there are several basic assumptions within the models, such as the habitat suitability adjustment curve that corresponds to various habitats. It was observed that the habitat suitability models require further research, testing and validation to improve confidence in the model output which will make them more effective tools for EFA (Tharme, 2003).

2.3.6 Holistic methods

The final category are the holistic methods, which estimate an EF regime based on ecological objectives or derived from the natural flow regime or by a combination approach. Holistic methods incorporate a combination of the previously described methods to derive EFR. Use of holistic methods began in the early 1990s. The South African Building Block Methodology (BBM) and the Australian Holistic Approach were among the first holistic methods developed. Both the BBM and the Holistic Approach are bottom-up methods that require intensive baseline data collection and expert input to estimate a flow regime based on identified ecological, geomorphological, water quality or social objectives.

A top-down approach known as the Downstream Response to Intended Flow Transformations (DRIFT) was developed from the BBM method. The DRIFT method gave importance to biophysical functions and estimated EF requirements to maintain the identified biophysical functions. Multidisciplinary team of researchers studied the effects and requirements of EF and developed the thresholds of EF values. These thresholds then formed as a source of the EFR.

Another category of holistic methods are those that rely solely on expert opinion. The Expert Panel Assessment Method (EPAM), the Scientific Panel Assessment Method (SPAM) and the Habitat Assessment Method (HAM) are three examples of expert opinion methods. EPAM was the first holistic expert opinion method developed based on data availability of fish, trees, invertebrates and geomorphology by a team of multidisciplinary scientific experts. SPAM was developed by improving the effectiveness and transparency of EPAM, and HAM is a combination of both SPAM and EPAM (King et al., 1999).

Another widely applied holistic method is the Instream Flow Incremental Method (IFIM). IFIM was developed in the early 1980's, and the model assesses the effect of different water management scenarios on river habitat. According to King et al., (1999), it contains a series of procedures and simulation programs such as River 2D, GIS and decision support systems, PHABSIM being the most well known and most commonly used tool within the IFIM. IFIM has been applied extensively worldwide in at least 20 countries (Lester et al., 2019)

Poff et al., (2010) developed a similar approach called the Ecological Limits of Hydrologic Alteration (ELOHA), but this framework was designed for implementing at the regional scale (province, large basin, country). The ELOHA framework is developed using gauged data and hydrological models. Based on the hydrologic foundation and geomorphic information, rivers are classified at each point of interest and the deviation from the natural flow regime is calculated at each of these points of interest. The ecological response to hydrologic alteration is then determined through expert input and ecological monitoring, which are further used to develop the instream flow regime. ELOHA framework considers the social and economic aspects while calculating EF, but they are not clearly discussed within the framework. While determining EF through ELOHA framework, the effective cost is high. It is found that several regulatory agencies are unwilling to incur this high cost to implement ELOHA (Richter et al., 2011).

2.3.7 Strengths and weaknesses of holistic methods

Holistic methods are particularly useful because they allow the ability to construct flows that sustain a wide array of riverine landscape components into the EFR. They also allow flexibility based on time and resources and can have strong ties to the natural flow regime. The main weaknesses of holistic methods are that they rely heavily on expert opinion (King et al., 1999; Tharme, 2003). Expert opinion is an excellent technique for determining answers to specific questions when data and resources are not available. However, expert opinion has been criticised by local regulatory authorities or water managers (Acreman et al., 2017).

2.4 Challenges of Determining EFR

The scientific community recognised that EFA is necessary for the effective protection and restoration of riverine landscapes. But, actual determination of suitable EFR in practice has been lacking severely (Richter, 2011). The barriers to determining effective EFRs have been attributed to several factors that can broadly be grouped into two categories; scientific and policy/legislative challenges.

2.4.1 Scientific challenges and potential solutions

The major scientific barriers to determine EFR include lack of data, uncertainty in models and flow-ecology response relationships. The lack of stream gauge data results in difficulty in characterising the hydrology of a system and hence, establishing an EFR regime can be a major challenge. By using hydrological models, an alternative stream gauge data is generated and used to produce hydrographs. However, by establishing the basic flow requirements associated with hydrological models, there can be a large degree of uncertainty (Poff et al., 2010).

Another major scientific challenge is quantifying the link between flow and ecological response. It is difficult to determine flow-ecological response relationships when there are multiple factors that play on aquatic ecosystems such as climate change and flow changes. It is also a difficult challenge to collect the data along the river at numerous locations on a small subset**.** Researchers are required to extrapolate the results from one river segment, reach or watershed to other areas where no data exist. It is a challenging task, since the characteristics of the rivers and streams naturally vary and each geographic area has its own unique characteristics that may require specific EFR. The future scenario for forecasting the results are also to be considered. Another scientific challenge is coordinating EFA research among multidisciplinary groups of researchers. The main challenges with multidisciplinary team are that they use different approaches as well as different vocabulary within each discipline. This creates a communication barrier as well as different opinions and raises questions on what is important and how the data should be collected. Some possible solutions to the challenges outlined above are to continue and conduct research which will improve the model certainty. Conducting research to improve the understanding of the quantitative link between hydrology and ecology will also reduce scientific uncertainty (Poff et al., 1997, 2000, Acreman, 2016)**.**

2.4.2 Policy and legislative challenges and potential solutions

A major policy challenge that exists within EFA is transferring the scientific knowledge into effective water policy. It is documented in the literature that a communication barrier exists at the scientist and resource manager levels, which leads to tension, conflict and misunderstanding and hence ineffective in calculating EFA. This is largely due to the fact that water managers need quick and specific flow requirements to fulfil their responsibilities, whereas researchers generally need to study a system for multiple years to obtain an answer that contains a large degree of uncertainty. In addition, results on EFR are generally not in the same format. For example, for researchers, the magnitudes of EFR changes according to timing and duration of flow with response to the ecology, whereas resource managers fixed EFR values with suitable thresholds and acceptable levels of ecological degradation (Acreman, 2016, Macnaughton et al., 2017).

In order to transfer the best EFA knowledge to the water managers from researchers, the researchers have to calculate the results efficiently by overcoming uncertainties and make a path to the decision makers. The decision makers should then incorporate this uncertainty results in a final EFR. The roles of the researchers and the resource managers have to be defined at the beginning of the project to avoid, solve and resolve the communication problems among the stakeholders (Acreman et al., 2017).

2.4.3 Scientific expert input for EFA

When data and resources are not available to assess EF, it is common to use expert opinion to calculate EF requirements. Experts of different disciplines including like hydrology, ecology and geomorphology are asked to provide their best estimation based on their knowledge and experience. Expert inputs are particularly useful for decision making in EFA where the understanding of flow-ecology relationships are limited (Nichols et al., 2017).

The scientific panel approach is conducted in a workshop format, where the team of scientist meet several times in the field and the office to discuss the project and make recommendations based on their area of expertise. Scientific panel assessments take approximately 6 months to a year to complete. The main advantage of expert panel assessments is that participants have an opportunity to discuss their perspectives and can generally come to a better understanding of the position of other panel members through dialogue. Some of the disadvantages are that interpersonal conflict can affect the results and there is a high amount of cost and time associated with this technique. In addition, this method requires a significant time of commitment from busy scientific experts who may not be able to commit to the project (Acreman, 2016, Nichols et al., 2017).

2.4.4 Key features of the methods

Existing methods of EFA are differing in input data, types of ecosystem requirements, the time needed for different applications, and the level of confidence. EFA depends on data availability and collection of significant amounts of geomorphological and ecological data and ranges purely from hydrological methods, to multidisciplinary, comprehensive methods (King et al., 1991; Brown et al., 2020). Table 2.2 broadly compares the four types of assessment methods of environment flow.

2.4.5 The choice of the right assessment method

Different methods of EFA are used for different purposes depending on the case of the study and type of issues to be addressed (water resources planning, monitoring, river restoration plan, etc.). However, studies have shown that no single environmental flow assessment technique will suit all social, economic, hydrological, and ecological contexts within a country (Harwood et al., 2018, Riestra, 2018). Multiple variables should be taken into account for the implementation of different EFA methods. In general, high-confidence and inexpensive methods may need to be monitored and reviewed. As a general rule, if effort and time increases, the spatial scale of assessments decreases and hence, it is necessary to focus on quantitative assessments. Therefore it can be stated that there is no one right way to assess environmental flows. The choice of methods is based on a case-by-case with specific requirements of a river ecosystem and surrounding livelihood. Techniques can be selected from simple (high risk) to complex (low risk) and can be based on intensity of water use, budgets, capacity, and time frame of a river (Riestra, 2018).

Table 2.2 Main features of the calculation methods

(L =Low confidence; M = Medium confidence; H = High confidence)

FEATURES								
Method	**ECOSYSTEM COMPONENTS ADDRESSED**	**DATA NEEDS**	**EXPERTISE**	**COMPLEXITY**	**RESOURCE INTENSITY**	**RESOLUTION OF OUTPUT**	**FLEXIBILITY**	**COST**
Hydrological	The whole ecosystem, non-specific.	L (Mainly desktop) Historical flow records (virgin or naturalized) Historical ecological data.	L Hydrological and Some ecological expertise.	L	L	L	L	L
Hydraulic	Instream habitat for target biota.	L-M (Desktop limited field) Historical flow records. Hydraulic variables of representative cross-sections of the reach.	L-M Hydrological and Hydraulic modelling. Ecological expertise.	L-M	L-M	L	L	L-M
Habitat Simulation	Primarily instream habitat for target biota. Some consider channel form, sediment transport, water quality, riparian vegetation, etc.	M-H (Desktop and field) Historical flow records. Numerous cross sections data, Suitability habitat data for target species.	H Hydrological Advanced level in hydraulic and habitat modelling.	M-H	H	M-H	M	H
Holistic	The whole ecosystem/ most individual components. Some consider the groundwater, wetlands, Estuary, floodplain, social dependence on ecosystem, instream and riparian components.	M-H (Desktop and field) Historical flow records. Many hydraulic variables multiple cross-sections. Biological data on flow and habitat-related requirements of all biota and ecological components.	H Hydrological Advanced and hydraulic Modelling. Habitat modelling in some cases. Specialist expertise on all ecosystems components and Social economic expertise.	M-H	M-H	H	H	H

2.5 Environmental Flows Research in the International Context

Environmental flow assessment studies have gained importance in the last few decades, concentrated only in the USA, Australia and South Africa. From the mid-1970s, methodologies were developed to define ecological flow in the river as reported in the literature (Tharme, 2003; Opperman et al., 2018; Liu et al., 2011). Outside of the United States, the documentation of the knowledge and establishment of EFA methods are limited. In many countries, newer methods were developed during the 1980's (e.g. Australia, England, New Zealand, and South Africa). Other parts of the world, including East Europe, and many Latin America, Africa, and Asia, did not carry out significant work in this field, with less publication and developments on this topic. The Canadian policy of No-Net-Loss of productive habitat (DFO 1986), New Zealand Resource Management Act 1991 and the Australian policy for water resources are some of the important actions taken to protect the ecological value of the rivers and the ecosystems in different countries that are widely recognised. Some of the studies that have been carried out on EFs internationally are reported here.

Junk et al., (1989) separated fluvial systems into three major zones; erosion, transport and deposition. This framework provides a broad scale perspective, grouping the upper reaches of a basin with generally steeper channel gradients and higher degrees of hill slope-channel coupling, as the erosional zone. This erosional zone is often associated with the term headwaters, which is defined by a small drainage area near the source of the drainage network.

Poff et al., (1997) and Eddy et al., (2017) clearly explain the comprehensive ecological principles of flow regime alteration. Kirk (2019) systematically investigated the impacts of flow diversions on Rocky Mountain streams in northern Colorado and observed no change in channel morphology outside of wider, pool-riffle channels (1-3% stream gradient), but observed width reduction up to 50% in these low-gradient reaches. Bohn and King (2000) found that streams with a gradient less than 1.5% were sensitive to decreased channel capacity, area and depth. Studies by Baker et al., (2016) showed that fine sediment accumulation and slow-flowing habitats increased downstream of diversions, an effect most prevalent on streams with slope less than 3%. These studies focussed solely on physical channel characteristics because of the location of diversion structures at breaks in gradient and ability to pass high flows that had difficulty detecting significant changes.

A case study for the river restoration planning using the environmental flow assessment for the Rhone River in France was carried out by Mishra et al., (2010) . Vollmer et al., (2018) discussed the use of freshwater for meeting the ecological and social needs and they suggested that fresh water ecosystem needs should be incorporated into water management policies.

Lloyd et al., (2003) examined 70 studies for relationships between ecological and hydrologic changes or geomorphological changes and reported that 87% of the studies documented that the variables are changing because of reducing the flow volumes. Seaman et al., (2016) used the DRIFT model to assess the environmental flow requirements for the Marromeu complex of the Zambezi delta. Their study includes trade-offs between hydropower generation and annual flood releases, water users and assessment of changes in flows.

The major scientific challenges in environmental flow assessment for South Africa Rivers were outlined by King and Brown (2006). They used flow duration curves to quantify the changes in the river flows and the impact on riverine uses. They concluded that the environmental flow assessment should be done early in the planning process of water development along with an analysis of the economic benefits of the scheme.

A five step process to derive the ecosystem flow recommendations for the Savannah River, USA was developed by Richter et al., (2006). Freeman et al., (2007) used the example of downstream eutrophication and coastal hypoxia which lowered secondary productivity of river systems, and reduced feasibility of freshwater biota. They proposed that the alteration of headwater ecosystems can change longitudinal exchanges of energy and materials in river segments, eliminating distinctive habitats and potentially decreasing ecological integrity across large spatial scales and, ultimately, causing global losses of biodiversity.

Sun et al., (2009) used a coupled hydrodynamic and salinity model to simulate the spatial distribution of salinity as a function of the variation in freshwater inflows considering oyster and crab as indicator species. They derived the annual environmental flows for high, medium and minimum objectives for the Yangtze River estuary.

Poff and Zimmerman (2010) reviewed a large number of papers published in the last five decades to demonstrate quantitative relationships between different types of flow alteration and environmental responses. In the 165 papers that were reviewed, 142 (86%) reported that response to streamflow changes decreases. They noted that for both the cases, changes happen highly, and observed that fish abundance and diversity record show steady decline.

A Standardised Runoff Index (SRI) which incorporates hydrologic processes that determine the seasonal loss in stream flow due to the influence of climate was derived by Mishra and Singh (2010). It was observed that on a month to seasonal time scales, SRI is a useful complement to Standard Precipitation Index (SPI) for depicting hydrological aspects of droughts.

It can be seen from these studies that the application of environmental flow assessment in different parts of the world is still is in its infancy and hence more studies are needed to explore this issue.

2.6 Environmental Flows Research in the Indian Context

Necessitated by highly varying tropical monsoon hydrology in India, a very large number of river valley projects have been constructed for irrigation, flood control and hydropower generation. Floodplains have been cut out by embankments along rivers. Land based infrastructure development activities continue to increase sedimentation. Because of rapid and unplanned urbanisation, industrialisation and agricultural intensification, rivers are getting higher discharges of domestic and industrial effluents, fertilisers and pesticides. Once the water has been diverted, then, for long stretches, rivers exist only as dirty, polluted nallahs or streams, acquiring a substantial flow only during a short span of rainy days. Out of the 30 river basins from all over the world that were identified as world-class priorities for the protection of water biodiversity, nine are in India. These basins are, Indus, Krishna, Cauveri, Narmada, Ganga-Brahmaputra, Pennar, Godavari, Tapi, and Mahanadi. All these river basins have undergone significant alteration, mainly due to flow fragmentation and control, except the Ganga-Brahmaputra (Jain and Kumar, 2014). Despite the growing awareness on environmental flow, many developing countries like India do not yet apply this concept and there are significant barriers in implementing the EF with the present water management practices. Indian water planning and management treat the water which was flowing into the sea as ‘wasted’ and more importance is given to control the river water flowing through the dams and other structures for social development. Moreover, India is facing a challenge of managing its limited water resources with high spatial and temporal variability. Similarly, many countries have the lowest importance for the water needs of an aquatic atmosphere. Even in the new National Water Policy (MOWR, 2014), priority for water allocation to "ecology" is listed as the fourth item. There are no studies on the relations between the flow and functioning of river ecosystems in India. Most of the Indian studies focus on various organisms and water quality without reference to flow regimes. Of late, due to the progressive degradation of the water environment in India, concern on environmental flow has started to gain strength. The concept of environmental flows in India was first initiated by the Central Water Commission (CWC) in 1992, with a term called “Minimum Flow” in the river, according to which the discharge in the river should not be less than the average of 10 days minimum flow in its natural state. This was assumed with a vision of sustaining the rivers for the cause of upcoming hydropower projects and other infrastructure projects, but over a period of time, it was realised that environmental flows should be considered from a broader and holistic perspective. However, for various reasons, the Government of India has not postulated any strong recommendation on environmental flows, except for Himalayan Rivers. A few studies that have been conducted till date on environmental flows in India are discussed below.

In 1999, the National Commission on Integrated Water Resources Development Plan (NCIWRDP) recognised the significance of the environmental flows, but again the commission was not very confident about the recommendation. The Commission pointed out that the knowledge base for making any approximate calculation of this requirement was very limited. The Commission suggested about 2 percent of the total national water requirements to be allocated for 'Environment and Ecology'. The values given were not referenced to rivers, wetlands or groundwater and were just bulk volumes for the entire country without any geographical specification. The NCIWRDP estimates do not appear to be based on any scientific reasoning.

The Supreme Court of India had highlighted on the issue of minimum flow in 1999 and ordered the Government of India to ensure a minimum flow of 10 m^3/s in the Yamuna River to improve the water quality. Since then, the need for minimum flow in rivers has been discussed at many forums but mainly in the context of water quality.

In May 2001, the Government of India established the Water Quality Assessment Authority of India (WQAA) to advice on minimum streamflow in rivers to preserve the ecosystem (Smakhtin, 2004). The WQAA reviewed the existing EFA practices and suggested that the practices adopted on environmental flow in other countries were unlikely to be applicable in India. This is due to the difficult trade-offs between environment and agriculture, high hydrological variability, expensive waste treatment, water disputes in between various states, etc. Again, in 2007, WQAA suggested that a simple method "Modified Tennant Method" can be adapted to estimate the minimum flow in rivers in India but again the authorities were not confident of the recommended figures. Year 2005–06 can be considered as a turning point when India started thinking seriously about environmental flows. In March 2005 an international workshop on Environmental flow was organised by the Ministry of Water Resources, Ministry of Environment and Forests, World Wildlife Fund (WWF) India, National Institute of Ecology and a couple of other organisations. The workshop recommended the assessment of the environmental flow regulation individually as the requirement differs considerably in different rivers and in different reaches. Later on, in 2008, WWF–India under the Hong Kong and Shanghai Banking Corporation (HSBC) climate partnership programme initiated a study on environmental flow assessment in the Ganga river basin with a vision to sustainably manage the river and water resources in a critical stretches and key sites in the Ganga basin. In continuation, the National Environment Policy (NEP) in 2006 discussed about "Freshwater Resources" and also called for Integrated Water Resources Management (IWRM) and environmental flows. In the same year, as an improvement in implementation, the Himachal Pradesh government mandated 15% of lean season flow as a precondition for upcoming hydropower projects. The International Water Management Institute (IWMI) initiated some environmental flow assessment studies and developed Global Environmental Flow Calculator based on global data sets of water flows. The first scientific attempt to assess the environmental flow for the whole India was made by Amarasinghe et al., (2005). This study was conducted based on the worldwide study by the Smakhtin et al., (2004), and designed for major river basins in India. Based on hydrological data simulated by a global hydrological model, quantity of environmental flow was approximately estimated as 25% of the total renewable water resources available in the country. Observed data and ecological data which were used in this approach were not taken from Indian rivers. It was estimated by representing one scenario of environmental management and assuming all the major river basins are maintained in "fair" conditions as described by Smakhtin et al., (2004). The evolving ecological flow work and reviewed desktop methods of EFA for major Indian River basins viz., Krishna, Cauvery, Godavari, Mahanadi and Narmada are studied by Smakhtin and Anputhas (2006). The study did not provide any recommendations for environmental water demand estimation but provided discussion on environmental flows and ecological water allocation. Morid, et al., (2007) attempted to introduce a prototype scoring system for the ecological status in Indian rivers and illustrated the same through its application in several major river basins, including Krishna, Cauvery, Narmada, and part of Ganga. They adopted the desktop environmental flow assessment method as described in Smakhtin and Anputhas (2006), which was based on a number of indicators reflecting both the ecological condition and sensitivity of a river. However, this method cannot be applied for estuarine regions. Significant and clearly visible disturbances associated with basin and water resources development including dams, diversions, transfers, habitat modification and water quality degradation were listed as the possible management perspectives. The studies by Smakhtin's group should be seen as a first step towards the development and guidance given for framing future national environmental flow tools and policies.

A project carried out by Wetlands International South Asia and other organisations identified four flow scenarios based on hydrodynamics and biological modelling for the Chilika Lake, one of the Ramsar sites in the State of Odisha in India. It concluded that maintaining the present levels of fresh water flows will result in an incremental benefit whereas reduction in freshwater flows will result in an incremental cost through losses in agriculture and fisheries (Ghosh et al., 2006).

Environmental flows are assessed by critically evaluating the applicability of existing approaches at various locations of Brahmani and Baitrarani river basins in India by Jha et al., (2008). The study estimated low-flow and high-flow discharges for ecological river maintenance and to assess suitable methodology for environmental flows assessment. Three approaches, viz., (a) Flow Duration Curves technique, (b) Indicators of Hydrologic Alterations (IHA) techniques using 32 statistical variables, and (c) Holistic approach considering water quality and ecological data sets, were used. Minimum environmental flow to maintain base flow and thus aquatic habitat in dry season were estimated to be in the range of 2 m^3/s to 5 m^3/s (Volume 0.17-0.43 MCM/day). Maximum environmental flow to retain flood magnitude, scour channel and vegetation, recharge river banks and flood plain were estimated to be in the range of 500-900 m^3/s (43.3 – 77.8 MCM/day) at Champua (upstream) and 2000-6000 m^3/s (173- 518 MCM/day) at Anandpur (downstream). This is required to be applied at least once. They also suggested suitable scientific approaches to provide values of environmental design flows at different locations of the two important water surplus basins. State Water Resources Agency (SWaRA), Uttar Pradesh and WWF (2009) provided recommendations for the environmental flow requirements for Himalayan Rivers. These requirements cover the principles, planning, policies, methodologies and practice.

Babu and Kumara (2009) studied the environmental flow requirement using Tennant method in the Bhadra River at Lakkavalli, Shimoga District, and Karnataka State, India. They carried out the study using both desktop analysis and field investigations by considering biophysical and socio-economic modules and concluded that more than 60% of downstream communities were severely impacted by irregular dry season water level fluctuations, which had resulted in the increasing in the livelihood occupations and migration level in the fishermen communities. River water quality was found to be deteriorating and livelihood support base of river ecosystem was shrinking.

Central Water Commission (CWC, 2007) carried out studies on minimum flows in various Indian rivers. The studies indicated that in case of Himalayan Rivers, the virgin flows are very high due to snow melt contributions. However, it may not be possible to maintain this condition in the lower reaches due to large scale existing utilisations. Therefore, CWC recommended different minimum flow criterion for Himalayan Rivers in mountainous reaches. CWC recommended that minimum flow should not be less than 2.5% of 75% dependable annual flow. One flushing flow during monsoon with a peak not less than 250% of 75% dependable annual flow is recommended (in m^3/s). However, the minimum flow for Bhagirathi River should be 13% of Annual Mean Flow or 14.69% of 75% dependable Annual Flow, while it should be 22.60% of Annual Mean Flow or 18.75% of 75% dependable Annual Flow for Alkananda River.

All these studies deal with river flow alone and considered various methodologies to restore and sustain the riverine ecosystem. India has several important regions including the Ganges–Brahmaputra delta, Mahanadi, Krishna, Godavari, Cauvery, Zuari, Kutch and Periyar at Kochi. Most of these rivers are dammed and the freshwater inflow into the estuary is severely limited. It is imperative to understand the impact of this limitation on the ecosystem and take remedial measures in the near future.

2.7 Conclusion

In this chapter, an overview of the literature on hydrological and environmental flow methods are presented. It is seen that anthropogenic activities are severely affecting the hydrological variables (i.e., frequency, duration, magnitude, extreme events and rate of change) along the river basins. Besides, climate change is expected to affect the magnitude and frequency of extreme events and likely to cause more intense and hydrological alteration. One of the measures to mitigate the hydrological changes is through the environmental flow and restoring the natural ecosystem in the river basin. Therefore, it is of great importance to understand the hydrological alteration at river scale. This research aims to (i) determine the hydrological alteration for Krishna River by removing the climate change impacts; (ii) assess the environmental flow requirements for Krishna River basin; (iii) analyse the hydraulic analysis through environmental flow requirements; and (iv) evaluate the hydraulic parameters through the suitability index curve to discovery the habitation index.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The study of environmental flow assessment for Krishna River is focussed towards discussing the current status of the flow with respect to the natural flow that was flowing before the construction of dams. The natural riparian vegetation, growth of rare and native species, changes in minor channel characteristics, etc., were either not observed or ignored during the construction. After the construction of the dam, the flow pattern gets altered resulting in irregular and low or high floods. During the dry seasons, the perennial rivers in arid and semi-arid regions are likely to turn as seasonal rivers. During the wet seasons, the water is stored in the reservoir area alone and this, in extreme cases, causes changes in the natural flow and the downstream habitat suffers the loss of water. The general climate in the Krishna River remains dry except during the monsoon months. About 90% of annual rainfall is received during the southwest monsoon period which is from June to September. Though there is contribution to rainfall from the northeast monsoon months of October to December, the quantity of rainfall is much less in this period.

The significance of the environmental flows concerns protecting the processes and resilience of aquatic ecosystems, and in turn, the goods and services provided to humankind. Environmental flow regimes allow hydrologic alterations up to some extent (Mathews and Richter, 2007). It is also well acknowledged that if environmental instream flows are altered too much, the function and structure of river regimes will change. The long-term alteration will have an influence on the physical, chemical, and biological properties of the river systems. For example, the changes in the magnitude, frequency and within-the-year variability of streamflow will potentially modify the physical aspects of habitat (Kiesling, 2003). The residence time of water would impact the chemical characteristics as well as the biological characteristics of the river water. As a result, the altered riverine components are very likely to break a healthy aquatic system. Studies on variation of the high flow are carried out to overcome the negative effects of floods and be prepared for dam breach and to take preventive measures. The maintenance of low flow regime concerns on the resilience of groundwater recharge, the base flow contribution and the various benefits related to the low flow. This chapter will describe the models and tools used for the study of hydrological alteration and environmental flow assessment. The models used in the EFA will be described to provide an understanding of their structure and limitations. Understanding the models and limitations of the tools are important as they will affect the reliability of the results of the flow assessment.

3.2 Study Area, Data Collection, Selection, Preparation and Organisation

The Krishna River, which has been chosen for the current study, is the fourth-longest river in India, with a length of about 1400 Km and having a catchment area of about 2, 60,000 km^2. Its catchment extends over four political states, viz., Maharashtra, Karnataka, Telangana, and Andhra Pradesh. Over 90 million people live in the Krishna River basin and more than 60 million of them depend on the river for their drinking water supply. Droughts and floods often affect the economy of the states lying in the river basin along with the loss of human lives. A large number of dams and reservoirs were built on the Krishna River and its tributaries between 1963 and 1999. The Narayanapur dam, constructed in the year 1983 and located in the middle of Krishna River, has a drainage area of 47,850 km^2. This dam was envisaged as a single purpose project meant for irrigation, but hydro-electric power generation and drinking water considerations in the downstream have complicated its management. The PD Jurala dam constructed in 1996 is located 185 km downstream from Narayanapur dam and is used mainly for irrigation purposes. The major dams along the lower Krishna River are the Srisailam and Nagarjuna Sagar Project (NSP), constructed in the years 1984 and 1968 respectively, and these dams play vital roles in flood control as well as reduction of sediment deposition in the downstream area in addition to producing power. Srisailam dam is located 210 km downstream of PD Jurala and 122 km upstream of NSP. One of the main tributaries of Krishna River is the Bhima River across which lies the Ujjani dam, built during the year 1980, to control flooding from tributaries and to provide water for irrigation. Due to the construction of a large number of dams on the main river and also across the main tributaries, the natural flow regime of the river significantly changed. Zero flow conditions were observed during many years in the lower Krishna River because of the rapidly increasing water used in the upstream.

To calculate the hydrological alteration, streamflow data of 5 gauge stations in the middle and lower Krishna River basin were used in the present study. These records were collected from Centre Water Commission and separated into reference (Pre-construction) and test impact periods (Post-construction) based on the timing of the construction of the projects (Table 3.1). The length of the streamflow records of the reference and test impact period varied among gauging stations. Information regarding dam type, dam location, start date of construction, reservoir size, power generation capacity and reservoir filling and operation, were also collected. The study area and the locations of dams are shown in Fig 3.1.

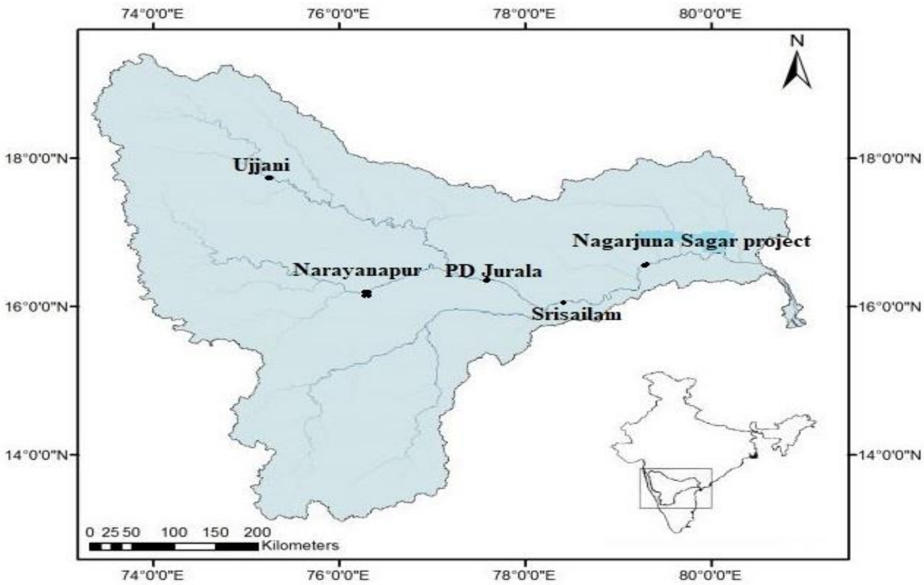


Fig.3.1 Study area and location of dams

Table 3.1 Major dams in Krishna River

S.No	Dam	River Reach	Down Stream Gauge station location (Data Available)	Reference Period	Test Period
1	Narayanapur Dam	Upper Krishna	De Sugur (1966-2015)	1966-1983	1984-2015
2	Ujjani Dam	Bhima	Yadgir (1965-2015)	1965-1980	1981-2016
3	P D Jurala	Middle Krishna	K. Agraharam (1971-2010)	1971-1996	1997-2010
4	Srisailam Dam	Middle Krishna	Nagarjuna Sagar Project (NSP) (1968-2015)	1968-1984	1985-2015
5	Nagarjuna Sagar Project (NSP)	Lower Krishna	Vijayawada (1960-2015)	1960-1970	1971-2015

The term *NSP is used for the gauging station and **Nagarjuna Sagar is used for the dam.

3.3 Removing of the Climate Variability Impacts on Hydrological Process

In the process of analysis to determine hydrological alteration, streamflow data for two different periods i.e., before and after dam construction were used. Streamflow data has the inherent variability due to the impacts of dam construction and climate variability. The impact of climate variability on streamflow in the study area needs to be removed before analysing hydrological alteration. Generally, the magnitude of climate variability is characterised by high and low flows which are described as wet and dry years respectively. If the annual precipitation is more than $P_{Mean} + P_{Standard\ Deviation}$, then the year can be called as a wet year, whereas, if the annual precipitation is less than $P_{Mean} - P_{Standard\ Deviation}$, then the year can be called as a dry year (Chulsang, 2006). Periods with annual basin precipitation in between $P_{Mean\ +\ Standard\ Deviation}$ to $P_{Mean\ -\ Standard\ Deviation}$ are considered as the normal years. Here P_{Mean} is the mean annual precipitation and $P_{Standard\ Deviation}$ is the standard deviation of annual precipitation. Thus, the streamflow records corresponding to the normal years are considered in the hydrological alteration assessment as shown in Fig 3.2.

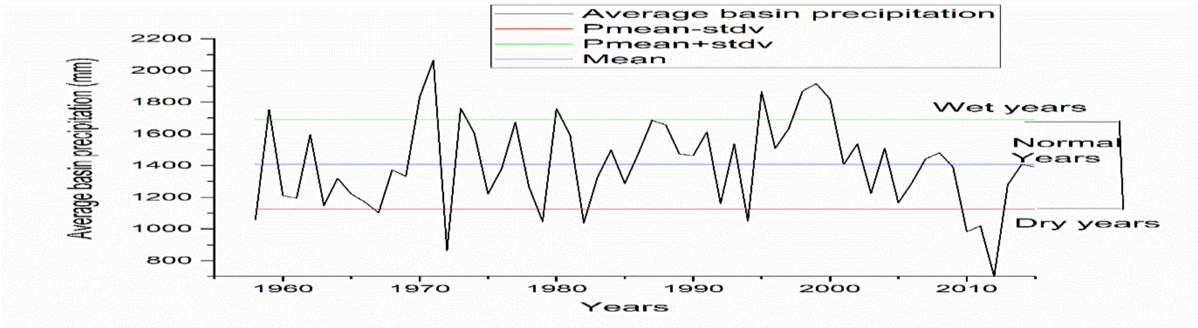


Fig.3.2 Water year separation of the streamflow time-series for Krishna River in the middle and lower basin

3.4 Modelling Systems used in the Research

This thesis presents quantitative assessments of long-term alterations in streamflow characteristics of the Krishna River and its tributaries and their capabilities for satisfying environmental flow standards in the river systems. The research combines five existing computer modelling systems. The IHA software developed by "The Nature Conservancy" is applied to perform statistical analyses of long sequences of daily observed flows to assess hydrological alteration. Environmental flow requirements (EFR) are calculated with the help of Desktop Reserve Model (DRM) and Global Environmental Flow Calculator (GEFC). DRM and GEFC are widely used tools worldwide. Flow Health model was used to evaluate the above two methods. The calculated EF are compared with the results obtained using Tennant method (1976), one of the most popular methods used worldwide. HEC-RAS, developed by the Hydrologic Engineering Centre (HEC) of the U.S. Army Corps of Engineers is used in the study to analyse the flow velocity, depth and wetted perimeter with the help of the calculated EFR. The existing flow status are compared with above methods. This comparative analysis will yield details on the physical status of the river over a period of time. Finally, habitat analysis is performed with the help of display flow data from the HEC-RAS. Fig. 3.3 shows the methodology of the research work.

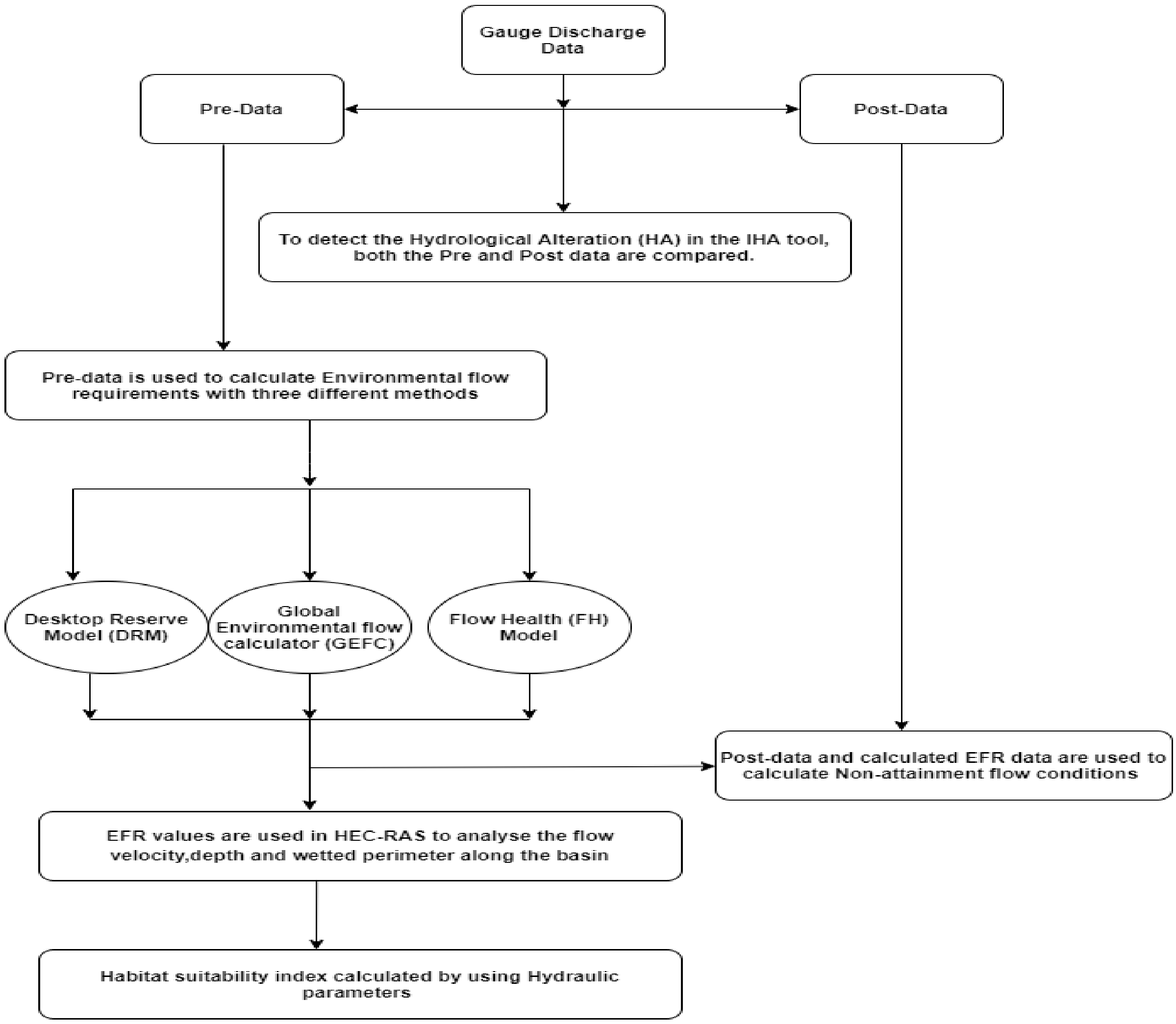


Fig.3.3 Methodology of the research

3.5 IHA Methodology

The IHA method is an open-access desktop model created by ‘The Nature Conservancy’ (2009) that calculates the 33 ecologically relevant parameters to characterise hydrologic regime which are grouped into five categories (Richter et al., 1997). The IHA approach is adopted for the research based on a literature review of available statistical analysis tools. Since, IHA is used extensively in this research, a description of the program functions and outputs are explained to understand the results and discussion of this study. The IHA provides flexibility for developing a large set of statistical metrics for analysing long sequences of daily time series variables relevant to ecosystem impact analyses. Streamflows in India are extremely variable with continuous fluctuations, seasonality, severe multiple-year droughts, and major floods that complicate analyses of long-term changes in flow characteristics. Conventional applications of the IHA are based on dividing a long historical record of observed daily streamflows into Pre-Impact and Post-Impact periods (Matthews and Richter, 2007). Comparative statistics are computed for the before construction versus after construction observed flow sequences to assess the impacts of water resources development by removing climate change impacts. A brief description of IHA and its components is given below.

IHA parameters which are based on five characteristics listed in Table 3.2 (Richter et al., 1997). The five categories contain the following:

(i) The first category contains parameters which indicate the mean magnitude of each monthly flow.

(ii) The second parameter group contains 12 parameters; due to the strong influence of extreme events on ecosystem, IHA focussed on measuring some characteristics of extremes events, such as timing of extremes (Julian dates), magnitude and duration of events i.e., 1-, 3-, 7-, 30- and 90-day maximum and minimum; zero flow days and base flow index.

(iii) The third parameter group describes the timing of the 1 day minimum and maximum.

(iv) The fourth parameter group comprise of the count and duration of high and low pulse counts. High and low pulses flows are user defined thresholds. The default thresholds for high and low pulses are set as median plus and minus 25% respectively;

(v) The fifth parameter group consists of the rise and fall rate of peaks and the number of times flow changes from increasing to decreasing and vice versa, which is known as the number of reversals.

IHA has been used to calculate and study the changes in flow regime due to the construction of the dam and its operation. IHA applied to pre- and post-dam periods, and then compare the 33 parameters between the two periods.

Table 3.2 Summary of hydrologic parameters used in the RVA and their features

Sl. No	IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
1	Magnitude of monthly water conditions	Mean value for each calendar month (12 Parameters)	• Provide habitation availability for aquatic organisms; • Maintain suitable temperature and dissolved oxygen in water • Soil moisture for plants; • Availability of water for terrestrial animals.
2	Magnitude and duration of annual extreme water conditions	Mean of a minimum and a maximum of 1-3-7-30-90 day, *Base flow Index and Number of zero days (12 Parameters)	• Formation of places for plants migration; • Purge invasive and introduction species from aquatic and riparian communities
3	Timing of annual extreme water conditions	Julian date of each a maximum 1-day and a minimum 1-day (2 Parameters)	• Enable fish to move to feeding and spawning areas; • Restore normal water quality; • Maintain water chemistry
4	Frequency and duration of high and low pulses	Number of low and high flow pulses within each year (2 Parameters) Duration of low and high flow pulses within each year (2 Parameters)	• Shape physical character of river channel; • Provide drinking water for terrestrial animals; • Provide feeding chances for organisms and fishes; • Recharge floodplain and increases water table;
5	Rate and frequency of water condition changes	Number of rises and falls of hydrograph (2 Parameters) Number of Reversals (1 Parameters)	• Drought stress on plants falling levels; • Entrapment of organisms on islands, floodplains; • Trigger of new phase of life cycle.

*Base flow index (defined as 7-day minimum flow/ mean flow for the year)

Another group of parameters available in more recent versions of IHA are the Environmental Flow Components (EFCs). There are five types of EFCs: extreme low flows, low flows, high flows, small floods and large floods (Fig 3.4). Thresholds are based on the user defined flow values and ranges of EFC magnitudes are assigned. The default thresholds are built on the user's knowledge on the flow-ecology relationship at the study site. For example, the default threshold for small floods is a return interval of 6 years which is generally accepted as bank full flow. Flows greater than this threshold have important ecological relevance related to floodplain inundation; for example, the floodplain being able to provide nursery area for fish. The frequency, duration, peak flow, timing and rates of rise and fall are calculated on an annual basis for each EFC (The Nature Conservancy, 2009).

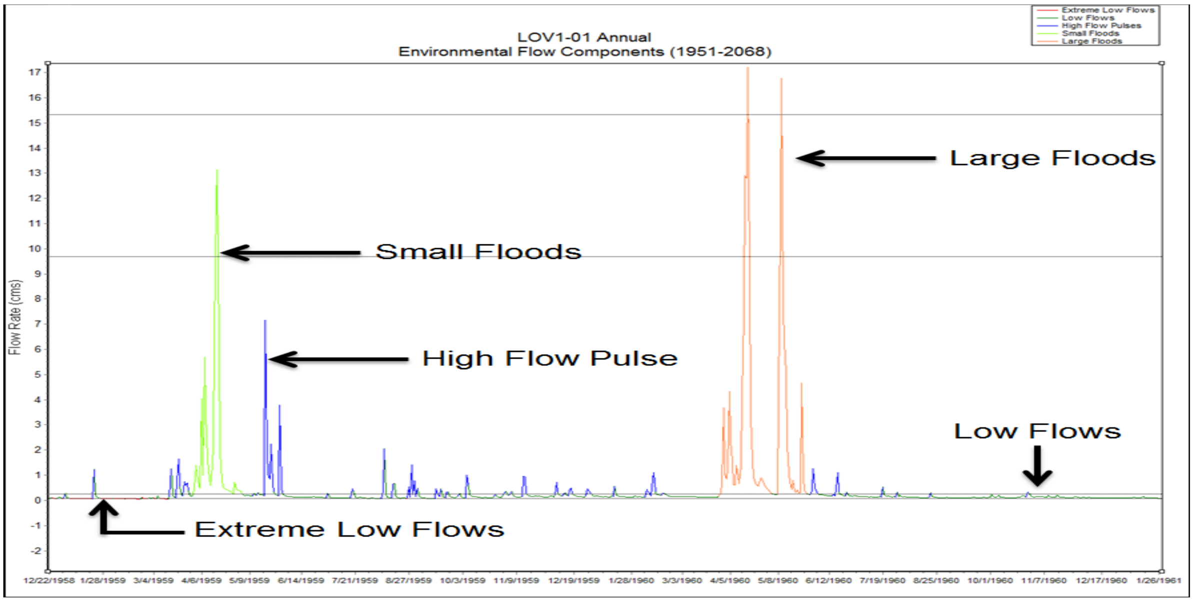


Fig.3.4 Example of EFCs calculated

The IHA allows for the calculation of parametric or non-parametric statistics. Non-parametric statistics are recommended due to the skewed nature of most hydrometric data. IHA can be used for characterisation of the hydrologic regime. The mean and the coefficient of dispersion, CD is calculated for each IHA and EFC parameter. The CD is calculated using Eqn. (3.1). For annual parameters, CDs are useful for determining inter-annual variability.

Coefficient of dispersion (CD) = (75^{th} percentile – 25^{th} percentile) / 50^{th} percentile (3.1)

Hydrologic alteration can be calculated within IHA by comparing pre and post impact hydrologic regimes. Various statistics are calculated to estimate hydrologic alteration. The deviation factor is calculated for the mean and CD of each IHA and EFC parameter using Eqn. (3.2) which corresponds to a percent change from the pre impact to post impact scenario.

Deviation factor = | Post impact value – Pre impact value |/ Pre impact value (3.2)

A statistic called the ‘significance count’ can be generated within IHA. This statistic helps to explain the validity of the deviation factor. To calculate the significance count, IHA randomly mixes all the pre and post impact years together 1000 times and calculates the deviation factor for the mean and also the CD for each random shuffle. The significance count is the fraction of times that the mean or CD was above the calculated deviation factor when years are not mixed. A low significance count (closer to 0) means that the deviation factor is significant and a high significance count (closer to 1) means that the deviation factor is not significant.

Another set of statistics that are generated to help explain the degree of alteration is the range of variability statistics (RVA). When RVA was incorporated into IHA, users were setting flow targets that maintained parameter values within RVA ranges such as the 25th and 75th percentile. Based on this range, three bins are created (0-25%, 25-75% and 75-100%). IHA calculates the number of annual values that fall within each bin for the natural regime (which will be roughly equal for each bin) and compares that to the number of annual values that fall within each bin for the altered regime. The degree of alteration is calculated for each bin as the percent difference between the observed numbers of values based on the natural regime and expected number of values based on the altered regime. IHA variables should be maintained such that annual values for parameters are equally distributed into the three statistical divisions, which accounts for the entire range of variability (Mathews and Richter, 2007; The Nature Conservancy, 2009). An example of the RVA approach and the calculations of hydrologic alteration for a period of record of 6 years are shown in Fig. 3.5.

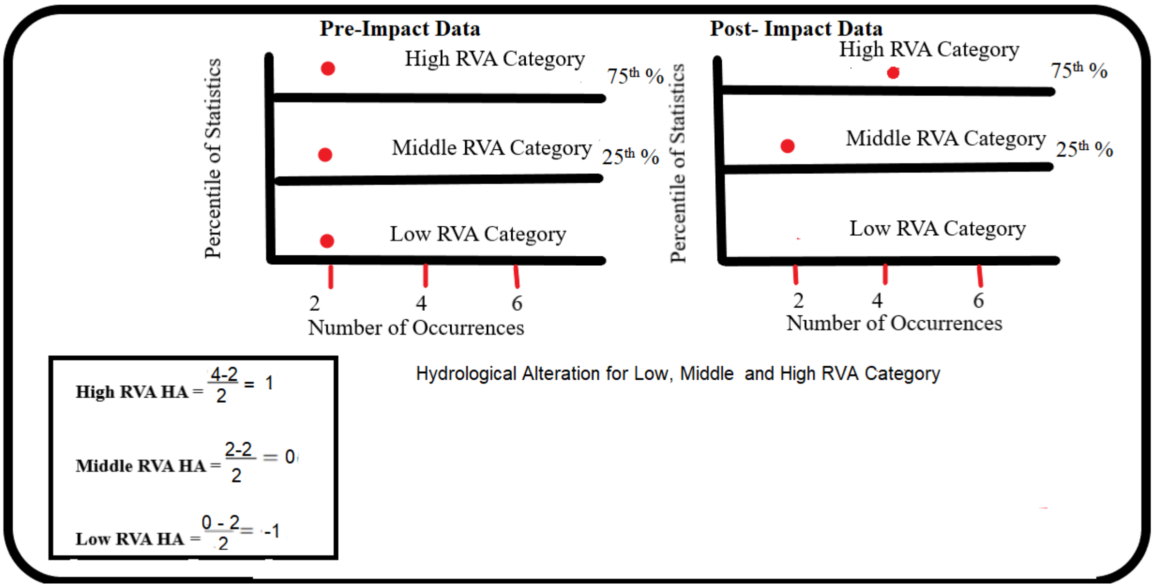


Fig.3.5 RVA approach and calculation of hydrologic alteration

3.6 Flow Health

To calculate the EF for each dam on the Krishna River, the Flow Health (FH) methodology, developed by International Water Centre, Brisbane is used (http://www.watersensitivecities.org). The methodology has four primary functions. In this section, the pre-impact period refers to a reference period and the post-impact period refers to a test period.

i) FH calculates the ecological importance in the form of nine hydrological indicators by using monthly inflow data based on the reference period and the test period of the dam. These nine indicators are calculated by comparing the flow of reference-period with flow of test-period, and output results are presented in the form of a score value. The score value of the indicators lies between 1 and 0, with score 1 representing close to the reference-period and score 0 representing away from the reference-period.

ii) Maximum monthly EFRs are calculated by assuming all the nine indicators score as 1 based on reference period data. This flow regime condition follows natural flow pattern but requires a high percentage of water.

iii) Derivation of EFR for each month will be based on score value in the (1 - 0) range.

iv) FH calculates additional flood frequency flow values for return intervals of 2, 4 and 6 years, which are to be released in one of the leading high flow months once in every return interval. It will help in the elimination of sedimentation and flushing of a river. The concept and ecological relevance of flow health indicators are explained in Table 3.3.

The best way to summarise the hydrology of the river and flow regime is by the of use flow duration curve (FDC), which is the graphical representation of discharge versus exceedance probability. The nine indicators are calculated using the FDC, based on the reference period and the test period. To calculate the FH scores for all the indicators, FDC of reference period and test period are compared from top to bottom. Based on the importance of the indicators, the threshold percentile for each indicator will be different. Scoring pattern and default thresholds are given in Fig 3.6. Before carrying out the work, the climatic parameters of FH tool must be adjusted to suit the study area, taking into consideration the geographical location. The present study is on the Krishna River which is located in the southern part of India where the wet season starts from June and dry season starts from January. Gippel et al., (2009) suggested an approach to select the indicators of FH software and this is explained below.

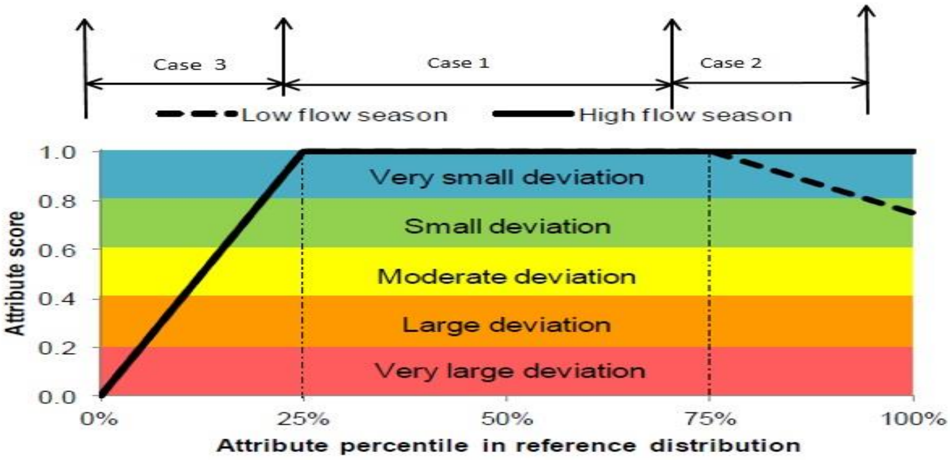


Fig.3.6 Scoring pattern for default thresholds

3.6.1 Low flow (LF) and lowest monthly (LM) flow

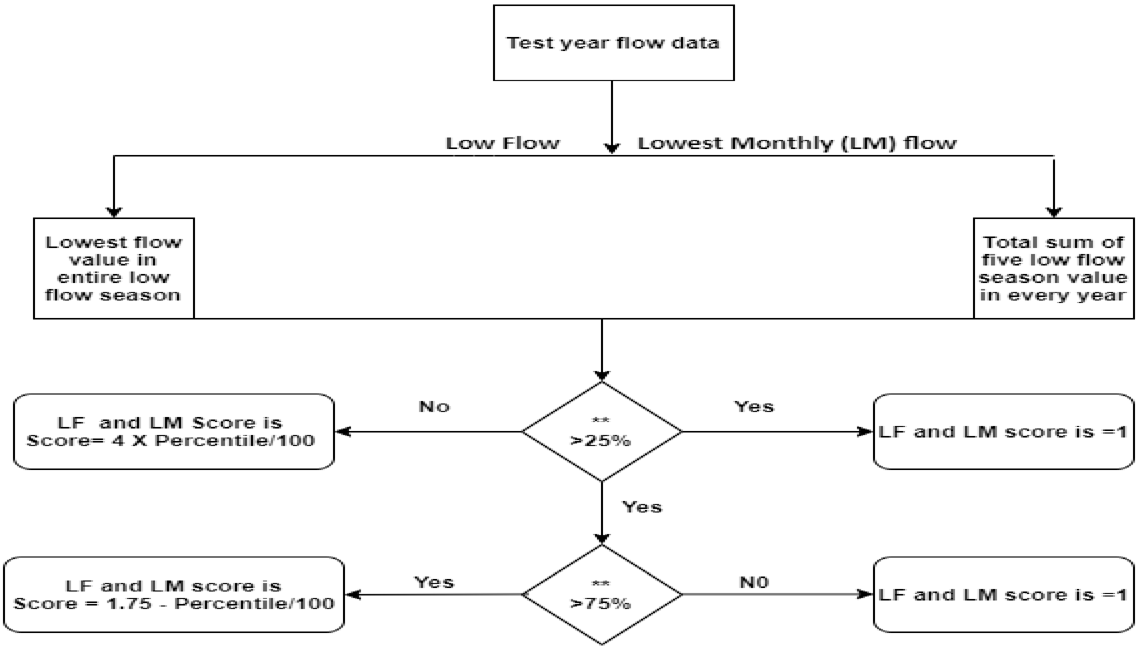
LF indicator score of the test year is calculated based on the sum of streamflow in the five low flow months' period (January–May) and its percentile lies in the reference period. The threshold percentile for LF and LM are taken between 25th percentiles to 75th percentile. The flows in the low flow season, i.e., above 75th percentile are considered as high flows and flows below the 25th percentile are consider as extreme low flows. Therefore, if the sum of the streamflow during the five low flow months' in a test year exceeds the 75th percentile value in the reference period, then the score is calculated by using Eqn. (3.3). If it is less than the 25th percentile value in the reference period, then the score is calculated by using Eqn. (3.4). If the value of the percentile reference distribution is in between the 25th and 75th percentiles, then the score will be '1'. The LM flow score is calculated in a similar way to the LF score but based on lowest monthly flow value of the year and its percentile lies in the reference period (Gippel et al., 2009). The flow chart given in Fig 3.7 (a) explains the working procedure for LF and LM periods.

If flow is greater than 75th percentile in low flow season,

$$\text{Low flow season score} = 1.75 - \frac{\text{Percentile}}{100} \tag{3.3}$$

If flows are less than 25th percentile

$$\text{Low flow season Score} = 4 \times \frac{\text{Percentile}}{100} \tag{3.4}$$



** The percentile values are fixed based on the reference period data

Fig.3.7 (a) Working flow chart of Low flow and lowest monthly flow

3.6.2 High flow (HF) and highest monthly (HM) flow

HF volume test year score is calculated based on the sum of the streamflow in the seven high flow months' (June–December) and its percentile lies in the reference period. The threshold percentile for HF and HM is taken as the 25th percentile because flows below the 25th percentile in high flow season are considered as low flows. If the sum of seven high flow months' values in the test year exceeds the 25th percentile value in the reference period, then the score is '1' and if it is less than the 25th percentile value of the reference period, then the score is calculated by using Eqn. (3.4). The HM flow score is calculated in a similar way to the HF score but based on the highest monthly streamflow value of the year and its percentile lies in the reference period. The flow chart given in Fig 3.7 (b) explains the working procedure for HF and HM flow conditions.

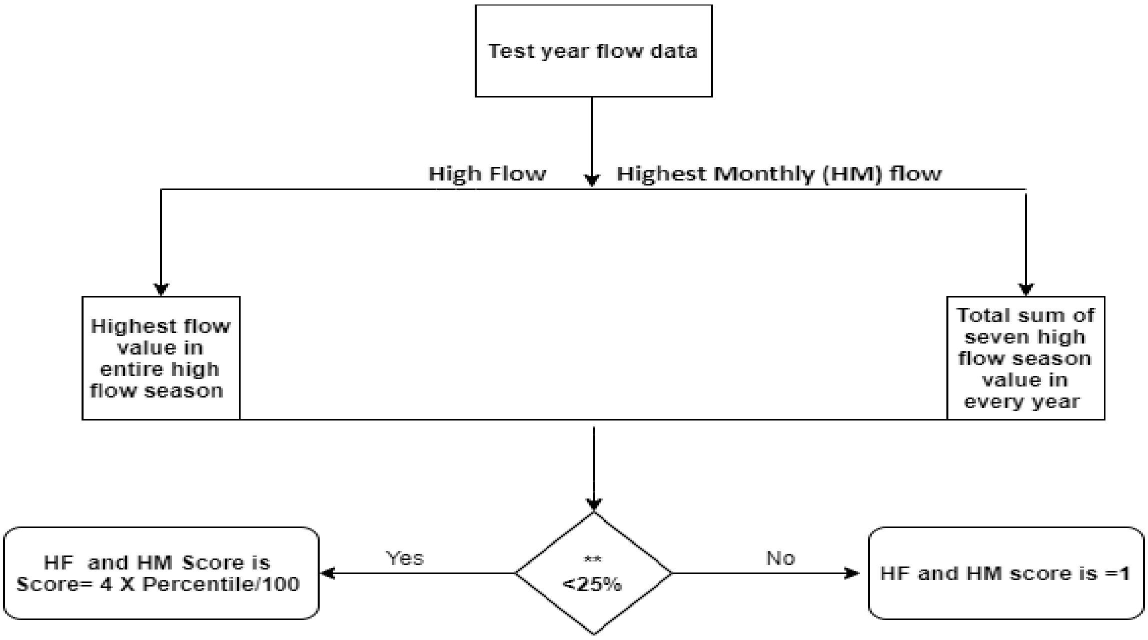
3.6.3 Persistently lower (PL) flow

The PL flow index is used to calculate the low flow effects for the entire year (12 months). The threshold percentile for PL is taken as the 25th percentile because flows below the 25% percentile are considered as low flows. During the reference period, if the flow in the test year exceeds the 25th percentile, then a value of '0' is assigned on a specific month. If the magnitude of flow is below the 25th percentile, then a value of '1' is assigned for that month. The score is '0' if the cumulative sum of the test year is 12 (if 12 months flow value falls below

< 25th percentile, it means then that the cumulative sum will be 12). If the cumulative total is less than or equal to '1', then the test year score is '1'. For the cumulative sum lying between 1 and 12, the score is calculated by using Eqn. (3.5). The flow chart given in Fig 3.7 explains the working procedure of PL flow.

PL, 1> cumulative total < 12

$$\text{Score}=1.0909 - 0.0909 \times \text{Cumulative total} \tag{3.5}$$



****** The percentile values are fixed based on the reference period data

Fig.3.8 (b) Working flow chart of high flow and highest monthly flow

3.6.4 Persistently higher (PH) flow

PH indicator is used to calculate high flow effects during the low flow season of five months (January – May). The thresholds percentile for PH flow is taken as the 75th percentile because flows above the 75th percentile occur mostly in the high flow season only; if they occur in the low flow season, they are likely to damage the ecology. During the reference period, if the test year monthly mean flow value in the low flow seasons exceeds the 75th percentile, then a value of 1 is assigned for that month. If the value of flow is below the 75th percentile, then a value 0 is assigned for that month. The positive score across the low flow season (5 months) is counted and if the cumulative total value of the test year is 5, then the score is '0'. If the cumulative total is less than or equal to 1 then the test year score is '1'. If the cumulative total is greater than 1 and up to 5, then the score is calculated by using Eqn. (3.6). The flow chart given in Fig 3.8 explains the working procedure of PH flow.

PH, 1 >cumulative total ≤ 5

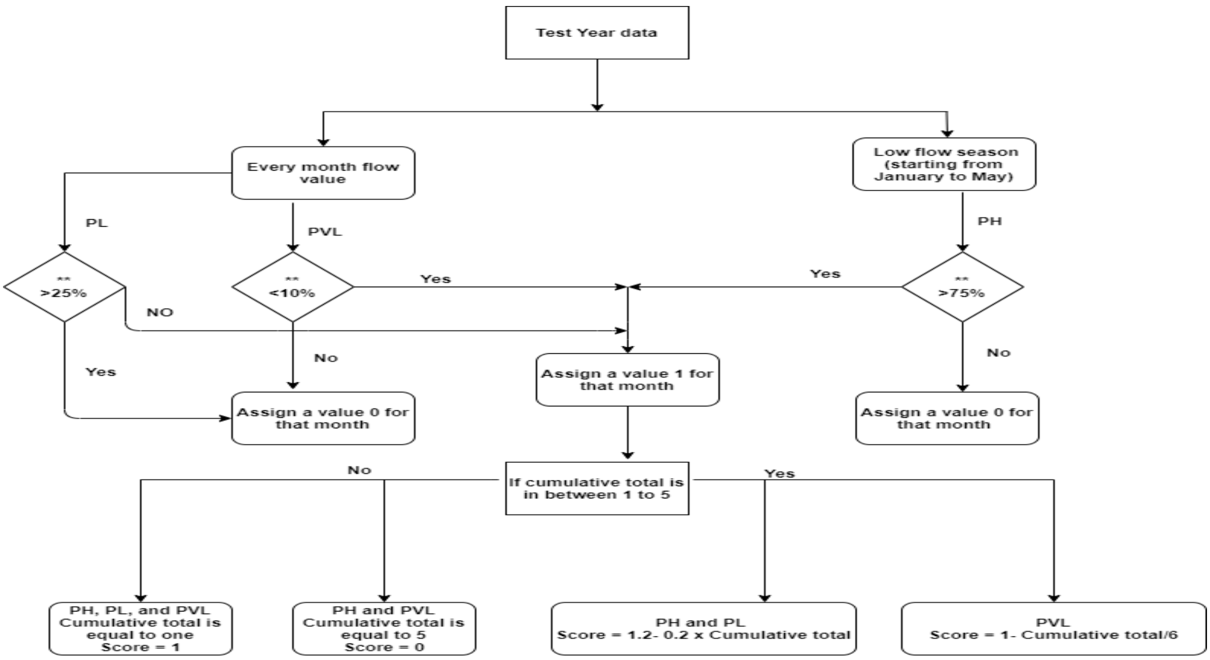
$$\text{Score} = 1.2 - 0.2\times(\text{Cumulative total}) \tag{3.6}$$

3.6.5 Persistently very low (PVL) flow

PVL score of the test year is calculated by assuming that the flow is less than or equal to the 10th percentile in the reference period. Below the 10th percentile, flows are the minimum flows which can maintain minimum water quality and oxygen levels in the river. If the monthly mean flow value in the test period is greater than the 10th percentile in the reference period, then a value of 0 is assigned, and if it is less than the 10th percentile, a value of 1 is assigned. The score is '1' if the cumulative sum of the test year is 1. If the cumulative total is greater than or equal to 6, then the test year score is '0'. For seasons having cumulative sum between 1 and 6, the score is calculated by using Eqn. (3.7). The flow chart given in Fig 3.8 explains the working procedure for PVL flow.

PV, 1 > cumulative total < 5

$$Score = 1 - \frac{Cumulative\ Total}{6} \tag{3.7}$$



****** The percentile values are fixed based on the reference period data

Fig.3.9 Working flow chart of PL, PH and PVL

3.6.6 Seasonality flow shift (SFS)

SFS indicator is used to calculate the shifting of flow during a season to other times of the year. By controlling the flow of rivers with barriers, seasonality of flow changes significantly. Therefore rank of the mean flow of each month in reference series and test series is assigned, highest being 1. The change in the rank between the two series is studied.

3.6.7 Flood flow interval (FFI)

The flow of FFI is used to calculate the return intervals of 2, 4 and 6 years, and used to select one of the return intervals in the model.

FFI case 1: If $N < 48$

$$\text{Score} = 1 \tag{3.8}$$

FFI case 2: If $N > 96$

$$\text{Score} = 0 \tag{3.9}$$

FFI case 3: If $48 < N < 96$

$$Score = 2 - \left(\frac{N}{48}\right) \tag{3.10}$$

N is the flood frequency in months and by default it is 48 months.

3.6.8 Environment flow modelling using flow health

Flow Health (FH) approach offers two techniques for computing environmental flow regime. These are the method of design flow and the method of minimal monthly flow. The minimum monthly flow technique determines the environmental flow regime based on accomplishing certain score for the nine indicators or total FH score. A flow regime that scores '1' on each indicator is the highest target. This would be a low-risk EF regime to the ecology. Such regimes, however, are difficult to follow. But the model can also be used to design EF regimes with lower Flow Health scores that certainly carry higher risk to the environment. The EF regime in the design flow method is designed to achieve a certain percentage of the mean reference flow per month.

The main purpose of introducing this method is to calculate EFR based on the nine most important ecological indicators. The advantage of FH tool is that one can see how much alteration can be reduced by considering the calculated EF, while the other two methods, viz., DRM and GEFC are not able to describe about it.

Table 3.3 Concept and ecological relevance of Flow Health indicators

Indicator	Calculation Method	Ecological Relevance
HF	Apply Eqn. (3.3) and (3.4)	Relates to Gross Habitat Area Availability
LF	Apply Eqn. (3.3) and (3.4)	
HM	Apply Eqn. (3.3) and (3.4)	Relates to the magnitude of flood flows and mobilising sediment for creation of physical habitat
LM	Apply Eqn. (3.3) and (3.4)	Minimum flows required for survival
PH	Apply Eqn. (3.5)	Primary production of benthic algae
PL	Apply Eqn. (3.6)	Colonisation of the stream bed by invasive vegetation or accumulation of the fine sediments
PVL	Apply Eqn. (3.7)	Loss of riffle habitats, temperature extremes crowding of organisms in pools.
SFS	Based on the rank of mean flow of each month in the reference period and the mean of the deviations in rank for test year	Barrier to stimulate the behaviour aquatic organisms
FFI	Based on a comparison of interval between floods in the reference and test periods, default flood frequency of 48 months (N). Apply Eqns. (3.8) to (3.10)	Seed dispersal and propagation, plants overgrowth on channels
Flow Health (FH)	Average the scores of above nine indicators with a modified LF which is the product of LF and PH	Overall ecosystem health

3.7 Desktop Reserve Model (DRM)

The DRM was developed by Hughes and Hannart (2003) for the South African region. Two different equations are developed to estimate the “Maintained Low Flow Requirements” (MLFR) and “Maintained High Flow Requirements” (MHFR), as given in Eqn. (3.11) and Eqn. (3.12). The total EFR is the combination of the MHFR and MLFR. MLFR is apportioned as maintenance low flow and drought flow. In calculating EFR, flow variability plays a significant role whereas within the model, two flow variability are used i.e., base flow index (BFI) and coefficient of variation of base flow (CVB). For calculating BFI, Q75 (75 percentile) value is taken from natural flow duration curve and this Q75 value is divided by the mean annual flow (i.e., BFI= Q75/MAF). Next, the CV is calculated by averaging the coefficient of variation

(CV) for three most important months during wet and dry seasons, which in the model are (July-Aug-Sep) and (Mar-Apr-May) respectively. This average CV is then divided by the BFI value to get a second variable CVB, which was used by Hughes and Hannart (2003) to calculate EFRs in the South Africa region. LP1, LP2, LP3, LP4, and HP1, HP2, HP3, HP4, are the desired environmental management class of (A, B, C, D) for low and high flow parameters.

Low flow requirements can be estimated by Eqn. (3.11)

$$MLFR = \frac{LP4+(LP1*LP2)}{(CVB^{LP3})^{1-LP1}} \tag{3.11}$$

High flow requirements can be estimated by Eqn. (3.12)

$$MHFR = \gamma \times HP2 + HP3 \tag{3.12}$$

If CVB > 15 then

$$MHFR = (\gamma \times HP2 + HP3) + (CVB - 15) \times HP4 \tag{3.13}$$

γ is a function of CVB and another desired environmental management class HP1 (Mazvimavi et al., 2007) which is given by:

$$\gamma = \frac{(\frac{Ln(CVB)}{Ln_{100}})^{HP1}}{HP1} \tag{3.14}$$

These model parameters were generated for South African rivers and the parameters have to be changed properly for conditions of different countries. The seasons in the model are inbuilt to suit South Africa’s climate conditions, where the primary wet season months are from January to March and dry-season months are from June to August. This presumption cannot be modified inside the model. However, for the Krishna River, the key months of the wet season are July to October, and for the dry season, the key months are from March to May. To reflect these key months to suit Indian conditions, the input data information was shifted by 6 months (i.e., January got to be July and so forth) and the outcomes were readjusted.

3.8 Introduction to Global Environmental Flow Calculators

Smakhtin and Eriyagama (2008) described Flow Duration Curve (FDC) based software package for desktop assessment of EFR. The method uses monthly flow data to build flow duration curve, by ensuring the elements of natural flow variability in the estimation of EF time series. The curve is developed for several classes of aquatic ecosystem protection from ‘largely natural’ to ‘severely modified’. The corresponding EFs progressively decrease with the decreasing level of environment protection. A non-linear data transformation procedure subsequently converts the calculated environmental flow duration curve into a continuous time series of environmental flows. The tool has facilities to zoom on a river basin, compute a variety of hydrological features, select any class of environment protection, compute the related environmental flow duration curves and time series and display both. The analyses can be carried out either using default (simulated) global flow data, with a spatial resolution of 0.5 degree, or a user-defined data file.

3.8.1 Methodology of Global Environmental Flow Calculator (GEFC)

The Global Environmental Flow Calculator (GEFC) method was introduced by Smakhtin and Anputhas (2006). In the GEFC, 17 fixed percentiles (0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99%) are used to cover the whole range of flow variability from top to bottom. GEFC can assess water requirements for six ecological management classes (EMCs) A, B, C, D, E, and F, where all the EMCs explain the different eco-friendly conditions of the river. These six classes range from unmodified to critically modified conditions, in which A and B are classified as an original and largely natural state, while classes E and F are classified as seriously and critically modified and environmentally unsustainable. Class D is set as the lowest allowable management condition, and Class C is classified as acceptable ecologically to maintain the ecosystem. For the 17 fixed percentiles, FDCs are developed. The first FDC is considered as original reference curve. Next, the EMC requirements are calculated by shifting of the original reference FDC by one percent. Finally, the EFR is calculated by dividing the total flow value of 17 fixed percentiles with each class by the mean annual flow and expressed as a percentage, which provides the percentage of MAF for each EMC. Table 3.4 describes the six ecological management classes. The natural flow values are the discharge values of post period of the five stations which are sorted monthly wise and the reference FDC is developed using the principle of probability of exceedance, that is for the probability of 0.01 is the flow value lower by 0.9999 times 1- (0.01/100). This is executed using the percentile function in MS Excel where the data array becomes the flow value. The five environmental classes are generated by lateral shifting of reference FDC towards the reference axis. This indicates that the flow which occurred with time of exceedance of 0.1% will be shifted to 0.01%. In simple case the flow value which used to occur l in 1000 years is made as the flow to be occurring once 1 in 10000 years. Hence, the highest flows are eliminated making way for low flows. In simple terms, it, it means that the class “A” EFR curve acts as a reference FDC for next class B. Similar shifting is carried out for remaining management classes. This is done for all the seventeen points of probability of exceedance 0.01, 0.1, 1, 5, l0, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9, 99. 99%. These points ensure that the entire range of flows is adequately covered.

3.8.2 Preparation of monthly standard environmental management classes

The historical environmental flow series, namely, A, B, C, D, E and F values obtained from the software are sorted month wise for each class. The average of the values is assigned as the monthly recommended EMC. The pre flow values are compared with this recommended EF values. The percentage of values which are less than the EMC for difference series, A , B, C, D, E and F are averaged to check for the better acceptable flow magnitude. The relation between various parameters is identified and the methodology is applied to Krishna River.

Table 3.4 Description of Ecological Management Classes (EMC) in GEFC tool

EMC	Ecological supporting condition	Acceptable water management issues
A: Natural	Natural rivers condition.	Protected rivers and basins. No new water projects (diversions, dams) permitted.
B: Largely natural)	Slightly modified from natural condition and supports important ecologically and biological activities in rivers and provided best habitation.	Small irrigation developments and Water supply schemes are allowable.
C: Moderately modified or "fair" condition	The habitats and dynamics of the biota have been distressed. Basic ecosystem functions are still undamaged.	Socio-economic development projects are accepted.
D: Largely modified	Large changes have occurred in natural habitats, biota, and basic ecosystem functions.	Significant and obvious impediments to the development of the basin and water resources, including diversions, habitat change, dams, transfers, and water quality deterioration.
E: Seriously modified Seriously and Critically	Habitat diversity and availability have failed. Ecosystems changed and basic ecosystem functions will fail. Significantly reduced species richness. Only tolerant species survive.	This status is not acceptable from the management perspective. Water management interferences are essential to restore flow patterns and to 'move' the river to natural or pre-construction conditions.
F: Critically Modified	Modifications have reached a critical level and the ecosystem has been completely modified with almost total loss of natural habitat and biota.	This status is not acceptable from the management perspective. Management interferences are required to restore flow patterns.

3.9 HEC-RAS Modelling

3.9.1 GIS Software

Creating the geometric data for hydraulic modelling is carried out in HEC-Geo RAS, which is an ArcGIS extension developed by the Environmental Systems Research Institute (ESRI). HEC-Geo RAS is capable of pre-processing geospatial data for creating a numerical model input file in the preferred format for the HEC-RAS model and post-processing the results in ArcGIS.

3.9.2. HEC-Geo RAS model

The geospatial hydraulic model extension HEC-Geo RAS is a group of ArcGIS compatible tools designed to process geospatial data to be used with HEC-RAS. The geospatial software significantly facilitates the pre-processing of the HEC-RAS input data and the post-processing of the simulation results. The pre-processing of the input data involves the generation of a geometric data file in ArcGIS that will be imported to HEC-RAS. The data file contains information on the river, reach, and station identifiers, cross- sectional cut lines, cross-sectional bank stations, and downstream reach lengths for the left over bank, main channel and right over bank, and cross-sectional roughness coefficients. Each piece of information is represented in ArcGIS by a RAS layer. The layers are created by using information extracted from a group of supporting datasets (e.g. aerial imagery, land use information, stream delineation shape files, and topographic maps) and from a DEM in the form of a Triangulated Irregular Network (TIN). Table 3.5 presents a list of the RAS layers created for pre-processing the HEC-RAS input data that are relevant to the present study.

The most relevant post-processing capability of HEC-Geo RAS for this study is the generation of geometric data. The process involves exporting the HEC-RAS simulation results to ArcGIS, where a TIN of the water surface profile is then generated. The model is performed by calculations on gridded data obtained from the water surface TIN and the digital terrain TIN. In other words, the delineation of the floodplain inundated area (terrain analysis) is basically performed by determining where the water surface grid is higher than the terrain grid. The remaining post-processing capabilities of HEC-Geo RAS include the visualisation of HEC-RAS simulation results associated with flow velocity, shear stress, and stream power.

Table 3.5 RAS layers created for Pre-Processing the HEC-RAS input data relevant to the present study

RAS Layers	Purpose
Stream Centre line	Computes the cross-sectional stations at each cross-sectional cut line.
Banks	Delineates the main channel conveyance area from the overbanks.
Flow Paths	Identifies the location of the centre-of-mass for flow in the channel, left over bank, and right over bank.
Cross-Sectional Cut Lines	Locates the cross-sections. Station-elevation data are extracted along the cut lines from the TIN.
Bridges/Culverts	Identifies the correct river station for the bridge or culvert. Station elevation data are extracted for the top-of-road for the bridge deck from the TIN.
Inline Structures	Identifies the river station for the inline structure. Station-elevation data are extracted for the top-of-weir profile from the TIN.

3.9.3 Description of HEC-RAS

HEC-RAS is a hydraulic modelling software developed by the U.S. Army Corps of Engineer´s Hydrologic Engineering Centre. HEC-RAS Version 4.1 is used in the present study. The software is capable of performing one-dimensional (1-D) steady and unsteady-flow simulations to perform hydraulic computations for a full network of river channels, including floodplains. In the study, the hydraulic model is used to calculate the depth and velocity in a river for calculated environmental flow in the river network of interest. The model is used for one-dimensional flow routing. In 1-D model, the flows in the river channel and the floodplains are treated in the longitudinal direction parallel to the channel. But in reality, the flow in a natural channel is never truly 1-D. In the 1-D HEC-RAS flow model, the geometry of the channel and the floodplains are represented by a series of cross sections along the reach. The application of more complex approaches, such as two-dimensional (2-D) and three-dimensional (3-D) models for large-scale study sites may be unfeasible due to data requirements, computational cost, and numeric uncertainties may arise throughout the process (Bravo et al., 2012).

HEC-RAS is capable of performing steady and unsteady flow simulations, sediment transport/mobile bed computations, and water quality analysis. The steady analysis components are used in this study. The steady flow component calculates water surface profiles for steady gradually varied flow. The computations are based on the solution of the 1-D energy equation, evaluating energy losses by friction through the Manning’s equation and by using contraction and expansion coefficients. Water surface profiles are computed from one cross-section to the next one by solving the Energy Equation with an iterative procedure (Bravo et al., 2014). The 1-D Energy Eqn. (3.15) and the Manning's Eqn. (3.16) are expressed as follows.

$$Z_2 + Y_2 + \frac{a_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^2}{2g} + h_e \quad (3.15)$$

$$Q = \frac{1}{n} A R^{\frac{2}{3}} S_f^{\frac{1}{2}} \quad (3.16)$$

where:

Z = elevation of the main channel invert; Y = water depth at a given cross-section;

V = cross-section averaged flow velocity; a = velocity weighting coefficient;

g = acceleration due to gravity; h_e = energy head loss; Q = water discharge;

n = Manning's roughness coefficient; A = flow cross-sectional area;

R = hydraulic radius; S_f = friction slope.

3.9.4 HEC-RAS model development

During this study, a HEC-RAS model was developed for the purpose of quantifying functional flows. CWC of India provides field data such as river cross sections and streamflow data. CWC measures the cross sections from left bank to right bank using echo sounder equipment. The total numbers of cross sections available for the Krishna River is 50 with an average survey chainage of 5 km. Water depths measured at these sites were used to calibrate the model. It is recognised that this is not the optimal dataset for hydraulic modelling, but due to the limited resources available for conducting field work, these data were considered as adequate to meet the main study objective of testing the framework for EFA. The primary objective of constructing the hydraulic model using the CWC data was to have a model that could be used to test and demonstrate EFA techniques for quantifying functional flows.

3.9.5 Data needed for model development

While using HEC-RAS, three main data inputs are required to build a model. First is the discharge or flow of water entering and exiting the model. Second is the Manning's n, the roughness coefficient representing the land's frictional resistance to flow derived from land use data. Third is the topography of the model area in the form of a digital elevation model (DEM), used to derive the irregular terrain on the bottom of the 1-D flow area grid. HEC-RAS models do not account for infiltration or evaporation, and hence, such data is not needed. Stations that have water level and river cross section data are selected for downstream boundary condition of the hydrodynamic model. Initially, the calculated EF requirements throughout the Krishna River Basin are used as a discharge data as input in the model. The Manning's n is typically represented in a model by land use and land cover (LULC) data. The LULC data were obtained from the Globe Cover 2009 global land cover map developed by the European Space Agency and then converted to Manning's n values. The LULC data and DEM were uploaded using RAS Mapper to create a terrain file and a land use file for the model to derive elevations and Manning's n values. For this model, a 10 m resolution DEM was used. The slope is derived from the DEM at each cross section by using elevation above sea level.

3.9.6 Extraction of river cross sections from DEM

River cross sections are the key inputs for hydraulic modelling of a river and its floodplain. The available measured cross sections are used for comparing the cross sections extracted with DEM. Adequate number of cross sections are critical to produce a good representation of the channel bed and floodplain especially if sudden change in river bed elevation is recorded. In most of the cases, extracted elevation of the river and flood plain match well with field measured values. It was found that on an average, the error between measured and extracted elevation of cross section was in the range of 2.3% in terms of mean percentage deviation.

3.9.7 Determination of Manning's n

By running a hydrograph through the model and comparing the water surface elevation versus varying Manning's n values and comparing those values to the field measured water surface elevations, it was found that the water surface elevation steadily decreased as Manning's n increased. Measured water surface values are relatively close to the different water surface elevations computed by the model. However, due to the possible surveying errors or incomplete definition of bed geometry, no conclusive results were arrived at. A value of 0.035 was assumed for Manning's n based on literature for further modelling. Several sources suggest that a value of 0.035 is appropriate (Bedient et al., 2008; Juan et al., 2017).

3.9.8 Model Calibration and Validation

Calibration and validation of the model are necessary and these are critical steps in numerical applications. Calibration is a test of the model with known input and output information that is used to adjust or estimate factors for which data are not available. Validation signifies a comparison of model results with independently derived results from experiments or observations. The calibration and validation accuracies of the model are assessed based on the error function given by Eqn (3.17). The statistical parameter called Root Mean Square Error (RMSE), is used between simulated and altimetry derived water level (Table 5). It can be seen that the error is acceptable and the results of the HEC-RAS modelling agree with the observed data.

$$RMSE=\sqrt{\sum_{i=1}^{n}\frac{(y_i-Ý_i)^2}{n}} \qquad (3.17)$$

Whereas, n is the number of observations

$y_1, y_2, y_3 \ldots\ldots y_n$ are predicted water depth and velocity values

$Ý_1, Ý_2, Ý_3, \ldots\ldots Ý_n$ are observed water depth and velocity values

Table 3.6 Average calibration and validation values on the downstream of the dams at different cross-sections

SL. No	Downstream of the dam	Calibration		Validation	
		RMSE		RMSE	
		Velocity (m/s)	Water Depth (m)	Velocity (m/s)	Water Depth (m)
1	Narayanapur	0.12	0.32	0.12	0.28
2	Ujjani	0.19	0.21	0.15	0.17
3	PD Jurala	0.21	0.28	0.18	0.15
4	Srisailam	0.13	0.34	0.11	0.10
5	Nagarjuna Sagar	0.12	0.31	0.10	0.08

3.10 Data Analysis

Excel sheet, Origin 8 and R-Software were used for analysis of the data, generating graphs and carrying out various statistical analyses. Maps were prepared using Arc GIS.

3.11 Summary and Conclusions

In this study the IHA approach is used to analyse the hydrological alteration along the basin with the help of 33 ecological parameters. The 33 parameters are estimated using the method called Range of Variable Approach. This study uses three models to assess the Environmental flow requirements at five gauging stations in the Krishna River to study the ecological integrity of the river. A combination of Arc GIS and HEC-RAS approach is used for studying the hydraulic parameters. Water depth and velocity are calibrated and validated based on the observed data. Based on the performance of these models, if found to be satisfactory, they can be used for generating and simulating to calculate environmental flow.

CHAPTER 4

HYDROLOGICAL ALTERATION DUE TO ANTHROPOGENIC ACTIVITIES

4. 1 General

This chapter describes the results obtained by carrying out analysis using the software IHA V7.1, individually for each of the five gauging stations. The IHA parameters provide flexibility for developing a large set of statistical metrics for analysing long sequences of daily time series variables relevant to ecosystem impact analyses. IHA parameters have been specifically selected for their close relationship to environmental functions, such as population dynamics and habitat suitability which are based on five characteristics of hydrology (magnitude, duration, timing, frequency and rate of change of flow). For IHA analysis, only normal years which are impacted by the dams are considered, as explained in Section 3.2, and the data impacted by the climate variability are removed for the analysis. Changes in flow regime and hydrological alterations are studied using IHA tools. The results of the analysis using IHA explain the changes in the 33 parameters, which are reflecting ecological and hydrological changes that occur along the Krishna River due to the anthropological activities under five groups as explained in the following sections.

4.1.1 Group 1: Magnitude of monthly streamflow

Pre-period and post-period monthly average flows and deviation factors of 12 months are presented in Table 4.1. The Table shows that the average monthly streamflow had decreased from June to December and had increased from January to May. Similar flow variability was observed along the basin. The mean monthly flow in the low flow season showed a significantly upward trend in the post-period. The largest positive relative increasing trend was observed in the low flow months, such as February, March, April and May. At the gauging stations Yadgir, NSP and Vijayawada, streamflow values increased during these months. These effects are less, comparatively for Agraharam and De Sugur stations. Mean annual flows (MAF) of the pre-impact period, for the months of February and March have increased by >250% in the cases of NSP and Vijayawada stations while for the months of January and April, the streamflow has increased by >100% of that of the post-impact period. The occurrence of high flows during the low flow season adversely affect the ecology of the river and those species that are seasonal found. In addition, the overall monthly streamflow changed more significantly in the lower reaches of the river than in the upper reaches. This is because of releasing water from the upstream for irrigation and hydro-power in the low flow seasons. Among the 12 months, December can be considered as a transition month, since this month depicts the change of flood period to dry period in this region. It can be seen that, along the Krishna River, the mean monthly streamflow had altered due to the construction and operation of dams. Decreasing river flow affects the flushing property and increases sedimentation deposit at one place. As a result, fish population decreases, leading to loss of breeding and nursery grounds. The largest decrease of 46.6% in MAF was observed at Agraharam station, while the lowest decrease of 28.3% in MAF was observed at De Sugur. At the remaining stations, viz., Yadgir, NSP and Vijayawada, the flow decreased by 36.2%, 31.93%, and 32.29% respectively. This indicates that MAF in Krishna River decreased by more than 30%. The most important driving force for the change in the streamflow regime in the Krishna River is the construction of dams to meet the growing demands of the increasing population.

Table 4.1 Mean monthly flow and Deviation factor (DF)

Month	**Stations**														
	De Sugur			**Yadgir**			**Agraharam**			**NSP**			**Vijayawada**		
	m^3/s		**%**	m^3/s		**%**	m^3/s		**%**	m^3/s		**%**	m^3/s		**%**
	Pre	Post	DF	Pre	Post	DF	Pre	Post	DF	Pre	Post	DF	Pre	Post	DF
Jan	40	50	25.00	45	32	-28.89	59	72	22.03	161	382	137.27	161	359	122.98
Feb	46	48	4.35	27	49	81.48	50	80	60.00	122	465	281.15	122	437	258.20
Mar	33	42	27.27	15	30	100.00	41	70	70.73	91	440	383.52	91	417	358.24
Apr	12	32	166.67	7	54	671.43	28	56	100.00	83	239	187.95	83	231	178.31
May	27	26	-3.70	15	110	633.33	26	53	103.85	86	109	26.74	86	105	22.09
Jun	383	142	-62.92	184	249	35.33	398	94	-76.38	480	169	-64.79	491	160	-67.41
July	2285	1338	-41.44	636	342	-46.23	2653	732	-72.41	2807	1038	-63.02	2693	1042	-61.31
Aug	3116	2128	-31.71	1119	643	-42.54	3647	2276	-37.59	4944	2795	-43.47	4781	2706	-43.40
Sep	1279	1014	-20.72	1105	704	-36.29	2194	1092	-50.23	3404	2354	-30.85	3386	2211	-34.70
Oct	433	634	46.42	955	367	-61.57	1409	1046	-25.76	2533	1759	-30.56	2453	1693	-30.98
Nov	130	109	-16.15	255	117	-54.12	292	153	-47.60	701	549	-21.68	686	528	-23.03
Dec	65	59	-9.23	100	114	14.00	90	80	-11.11	263	370	40.68	253	359	41.90

DF (Deviation Factor) = ((Post-Pre)/Pre)*100; Pre=Reference impact period (Before dam construction); Post = Test impact period (After dam construction)

4.1.2 Group 2: Magnitude and duration of annual extreme conditions

The 1-day or multi-day minimum and maximum are represented by the lowest and highest single daily or multi-day average flow value occurring during the year. The mean magnitude of high and low water extremes of various durations provide measures of environmental stress and disturbance during the year; such extremes are necessary to trigger reproduction of certain species. Extreme high and low flow regime events play important roles in maintaining the structure and function of the rivers. The magnitude and duration of annual extreme water conditions for minimum and a maximum of 1-3-7-30-90 days for all the stations are shown in Table 4.2.

The results for Yadgir showed that frequency of stream low flow availability in the Krishna River has been mostly affected. The 1-, 3-, and 7- day minimum flows have significantly decreased from pre-impact to post-impact period with a negative deviation factor. Daily, weekly, monthly and seasonal mean low flow situations are altered drastically, whereas 1-day, 7-day and 30-day minimum mean flow statistics were reduced by more than 26%. Seasonal mean low flow volume increased from 0.39 m^3/s to 0.48 m^3/s (i.e., 21.18 % increase), due to hydropower actions taking place. Similar to this, 1-day, 3-day and weekly maximum flood flow statistics have altered negatively by around -11.81% with a decreased inflow. Monthly and 3-monthly maximum flows have also reduced up to -31.54%, due to possible upstream water diversion scenario.

A huge alteration is observed at Agraharam, i.e., 1 day, 7-day and 30-day minimum mean flow statistics have reduced (by more than -69.36%). Seasonal mean low flow volume has decreased from 26.25 m^3/s to 25.56 m^3/s (-2.64% decrease). This showed that the seasonal mean minimum flows reduced marginally after the construction of dams. Similar to this, 1-day, 3-day, 7-day, monthly maximum flow statistics have also altered positively by around 16.86% with an increase inflow. The reduction of 3-monthly maximum flow is due to the possible upstream water diversion scenarios in the river. These deviations were relatively small when compared to Yadgir.

De Sugur station showed a positive variability in daily, weekly, monthly and seasonal mean low flow situation. Minimum 1-day, 7-day and 30-day mean flow statistics have increased (i.e., more than 90.01%). It is observed that the 90-day mean low flow volume had increased from 14.06 m^3/s to 25.27 m^3/s (i.e., 79.73 % increase), which showed that the seasonal mean minimum flows have increased in the post-impact years. Similarly, a negative deviation of monthly maximum flow was seen for the 1-day, 3-day, and 7-day with a value around 11%. 3-monthly maximum flows had reduced from 2067 m^3/s to 1678 m^3/s. This showed that these flows got reduced after the impact year (due to more water obstructed).

For NSP station, 1-, 3-, 7- day minimum flow showed a significant decreasing trend after the construction of Srisailam dam. The average deviation factor of these parameters is -4.65 m^3/s (-47.79%). This showed that these flows are not appearing after the impact years. The 30-day and 90-day minimum mean flow increased from 33.70 m^3/s to 56.51 m^3/s and 72.50 m^3/s to 213.60 m^3/s respectively. The seasonal minimum flow increased which showed that it not only increased but also became highly variable after the construction of the Srisailam dam. Similar to this, maximum flood flow statistics for 1-day, 3-day, 7-day, 30-day and 90-day have been negatively altered with a decrease of average flow rate by 16.67%. This showed that these flows got reduced after the impact year.

Vijayawada station showed a positive alteration in daily, weekly, monthly and seasonal mean low flow. The seasonal mean minimum flows showed reduced values after the dam construction. Similar to this, 7-day, 30-day, 90-day, monthly maximum flood flow statistics showed an average negative alteration of 20.26%, indicating decreased flow. 1-day maximum flows increased by 6.67%. These deviations were relatively smaller when compared to all other stations.

The base flow altered negatively at Yadgir, NSP and Vijayawada stations, with a DF values of -67%, -51% and -56% respectively. Average value of DF for five stations are shown as -47.2 % which indicates that the potential discharge volume is decreased in Krishna River. The long span of decrease in base flow can change the ecology of the watershed. Base flow in the downstream is reduced. During most of the years, the river did not support the base flow, which indicated that there was no flow in the river. As reported in Poff and Zimmerman (2010), this decrease in the magnitude of low flow values and loss of low flow variabilities has a potential to disrupt species life cycles, reduce species richness and diversity, alter assemblages and dominant taxa, and increase invasive species.

In the view of IHA results, it is found that minimum extreme flow conditions have been more impacted than the maximum flow conditions. This can create an imbalance of competition and stress-causing organisms and create sites for plant colonisation. This may create a serious effect on river channel morphology and physical habitat conditions. Very low flow in winter possibly will create lower soil moisture condition causing water stress in plants. The long duration of these stressful conditions may possibly disturb the plant communities.

Table 4.2 Magnitude and duration of annual extreme conditions

Parameters	Stations														
	De Sugur			Yadgir			Agraharam			NSP			Vijayawada		
	m³/s		%	m³/s		%	m³/s		%	m³/s		%	m³/s		%
	Pre	Post	DF	Pre	Post	DF	Pre	Post	DF	Pre	Post	DF	Pre	Post	DF
1-day min	3.81	6.21	62.99	0.18	0.12	-33.33	11.65	1.82	-84.38	0.64	0.00	-100.00	2.17	9.93	357.60
3-day min	4.07	7.20	76.90	0.19	0.13	-31.58	12.19	2.11	-82.69	4.79	3.45	-27.97	2.29	11.43	399.13
7-day min	4.46	8.04	80.27	0.20	0.14	-30.00	12.88	2.43	-81.13	12.40	10.49	-15.40	2.67	14.24	433.33
30-day min	6.77	15.34	126.59	0.27	0.23	-14.81	16.35	9.39	-42.57	33.70	56.51	67.69	3.97	34.32	764.48
90-day min	14.06	25.27	79.73	0.39	0.48	23.08	26.25	25.56	-2.63	72.50	213.60	194.62	8.30	71.96	766.99
1-day max	7102.0	6860.00	-3.41	7.35	6.41	-12.79	8971.00	10370.00	15.59	10950.0	10470.00	-4.38	10020.0	10690.00	6.69
3-day max	6807.00	6261.00	-8.02	6.79	5.98	-11.93	8266.00	9623.00	16.42	10200.0	9585.00	-6.03	9165.00	9170.00	0.05
7-day max	6006.0	5321.00	-11.41	5.91	5.27	-10.83	7048.00	8169.00	15.91	9048.00	8058.00	-10.94	8044.00	7297.00	-9.29
30-day max	3399.0	2945.00	-13.36	4.09	3.61	-11.74	4154.00	4966.00	19.55	5642.00	4362.00	-22.69	4697.00	3717.00	-20.86
90-day max	2067.0	1678.00	-18.82	3.20	2.57	-19.69	2723.00	2674.00	-1.80	4032.00	2447.00	-39.31	3023.00	2096.00	-30.66
Base flow	2.47	1.67	-32.39	1.75	0.98	-44.00	9.34	7.64	-18.20	9.54	4.67	-51.05	10.54	4.58	-56.55

DF (Deviation Factor) = ((Post-Pre)/Pre)*100; Pre=Reference impact period (Before dam construction); Post = Test impact period (After dam construction)

4.1.3 Group 3: Timing of annual extreme water conditions

Two parameters are considered under this group, viz., the 1-day annual minimum and 1-day maximum water condition measured in Julian calendar. The timings of the highest and lowest water conditions within annual cycles provide a measurement of the critical period which causes an environmental disturbance. Key life-cycle phases (e.g., reproduction) is intimately linked with the timing of annual extremes; thus anthropogenic changes in timing may cause reproductive failure, stress and mortality.

Timing of low flow showed that the Julian date of low flow and high flow occurrence shifted in Krishna River. Results of the study for all the stations are shown in Table 4.3.

- At Yadgir station, date of occurrence of low flow shifted by 16 days forward, whereas the date of high flow shifted by 2 days forward.
- At Agraharam station dates of occurrence for both low flow and high flow are shifted by 16 days forward.

- At De Sugur station date of occurrence of low flow was shifted forward by 29 days, whereas the date of high flow also shifted forward by 21 days.
- NSP station showed that low flow occurrence date was shifted forward by 36 days, and high flow date shifted forward by 15 days.
- At Vijayawada station the low flow occurrence shifted forward to 24-days, whereas high flow occurrence shifted by one month (30-days).
- In Krishna River, average low and high flow occurrence got shifted forward by 24 and 17 days respectively. The alteration of annual extreme conditions (high and low flow) produces water stress in organisms.

Table 4.3 Timing of annual extreme water conditions (Julian Date)

Parameters	**Stations**														
	De Sugur			**Yadgir**			**Agraharam**			**NSP**			**Vijayawada**		
	Pre	Post	DF	Pre	Post	DF	Pre	Post	DF	Pre	Post	DF	Pre	Post	DF
Date of minimum Flow	122	151	23	128	144	12	146	163	10	121	157	29	141	165	17
Date of maximum Flow	209	230	9	247	248	0.19	226	242	7	231	246	6	222	251	13

DF (Deviation Factor) = ((Post-Pre)/Pre)*100; Pre=Reference impact period (Before dam construction); Post = Test impact period (After dam construction

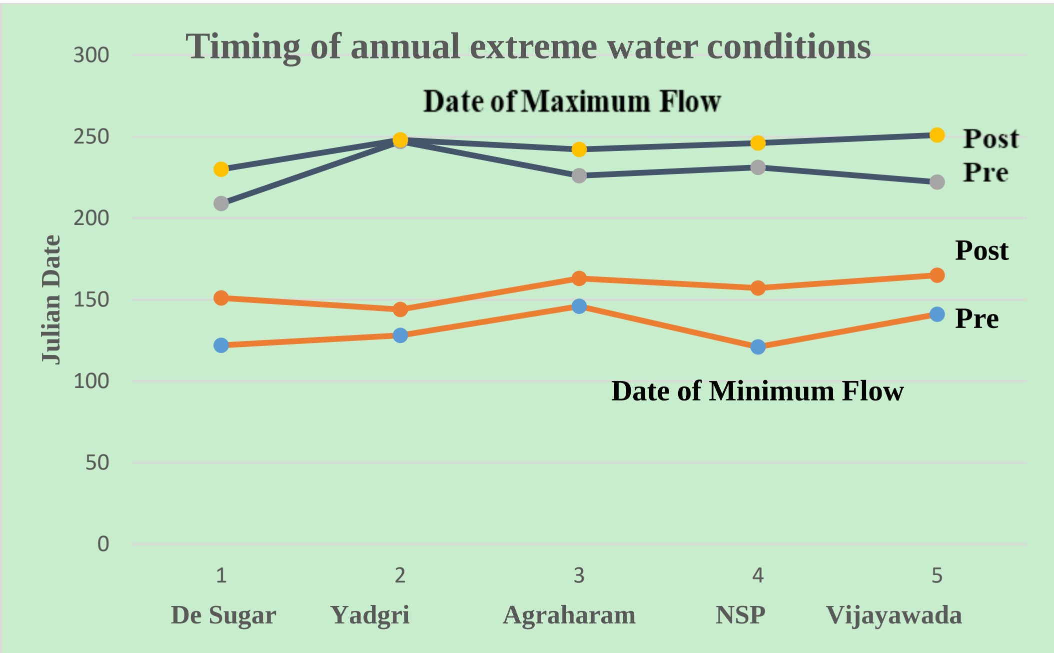


Fig 4.1. Timing of annual extreme water conditions

4.1.4 Group 4: Frequency and duration of high and low pulses

The fourth group of parameters measures the number of annual occurrences of water condition pulses that exceed an upper threshold or remain below a lower threshold, and measure the mean duration of such high and low pulses. This group measures the frequency and duration of high and low water conditions to show the pulse behaviour of environmental variation within a year. Hydrologic pulses are defined here as those periods within a year in which the daily mean water condition either rises above the 75^{th} percentile (high pulse) or drops below the 25^{th} percentile (low pulse) of all daily values.

The low flow pulse count increased at Yadgir, Agraharam and De Sugur station (Table 4.4). At NSP and Vijayawada stations, it is decreased by 33% and 61%. From the Table 4.4, it can be seen that the high flow pulse count decreased at Yadgir, NSP and Vijayawada station by 16%, 32% and 40%, whereas at stations Agraharam and De Sugur it is marginally increased by 8 to 9%. These variations affect the frequency and magnitude of soil moisture stress for plants and the availability of floodplain habitat for aquatic organisms. These alterations also disturb duration of substrate disturbance, channel sediment distribution, and bed-load transport, (Pietrzykowski and Daniels, 2014).

4.1.5 Group 5: Flow rate and frequency

Group 5 considers the rate of rise and fall in streamflow which measure the mean rate of both negative and positive changes in water conditions. The frequency and rate of change in flow described the sudden deviation in flow (any flow) and a number of intra-annual cycles of environmental variation. It can also provide a measure of the frequency and rate of environmental change within a year. From the Table 4.4, it is observed that the rise in flow rates for gauging stations at Yadgir, Agraharam, De Sugur, and NSP showed a negative value with a DF of -26.01 %, -14.5%, -9.2%, and -18.7% respectively. It is found that the trend in flow rate is in positive with a DF of 13.5% at Vijayawada station. From the results, the fall rate is found to have a decreasing trend with a DF of -5% and -6% at Yadgir and NSP stations respectively. For the stations at Agraharam, De Sugur, and Vijayawada, the DF values showed an increase of 15%, 10.7% and 24% respectively. It is found for Krishna River that the average rise rate decreased from 177 m^3/s/day during the Pre impact period to 151 m^3/s/day during the Post impact period and fall rate increased changed from -145 m^3/s/day to -171 m^3/s/day. This type of changes create desiccation stress and drought stress on plants on low-mobility stream edge organisms (Nie et al., 2019).

4.2 Hydrological Alteration

After studying the deviation factor of the each parameter between pre impact and post impact year, further analysis were carried out using the RVA and Hydrological alteration (HA) approach as explained in section 3.2.The three categories for RVA were the low RVA, middle RVA, and high RVA, where the upper (high RVA) and lower (low RVA) boundaries were set as ± 1 standard deviation from the mean for the analysis. The middle RVA boundary is set in between low RVA and high RVA. The upper and lower RVA categories are not considered in this study because most of the flows occur in between 25th % to 75th % percentile flow. The results of hydrological alteration for middle RVA category are shown in Table 4.5. The values shown indicate the degree to which the RVA target range is not met for the selected intra-annual hydrological parameters.

Table 4.4 Frequency and duration of high and low pulses

Parameter	**Stations**														
	De Sugur			**Yadgir**			**Agraharam**			**NSP**			**Vijayawada**		
	m^3/s		**%**	m^3/s		**%**	m^3/s		**%**	m^3/s		**%**	m^3/s		**%**
	Ref	Test	DF	Ref	Test	DF	Ref	Test	DF	Ref	Test	DF	Ref	Test	DF
Low pulse count	4.10	7.40	80.49	0.10	0.60	500.00	4.60	15.20	230.43	23.80	15.90	-33.19	7.00	2.00	-71.43
Low pulse duration	30.20	15.00	-50.33	3.50	16.90	382.86	26.50	8.90	-66.42	3.90	5.60	43.59	17.00	29.00	70.59
High pulse count	4.40	4.80	9.09	5.50	4.60	-16.36	4.40	4.80	9.09	4.90	3.30	-32.65	5.00	3.00	-40.00
High pulse duration	8.90	6.20	-30.34	9.90	6.90	-30.30	8.60	6.80	-20.93	11.60	5.60	-51.72	12.00	6.00	-50.00
Rise rate $m^3/s/day$	170.30	154.60	-9.22	0.30	0.30	0.00	258.80	221.20	-14.53	280.50	228.00	-18.72	239.00	271.00	13.39
Fall rate $m^3/s/day$	-108.30	-1120.00	934.16	-0.10	-0.10	0.00	-157.60	-181.00	14.85	-237.20	-222.50	-6.20	-1711.00	-211.00	-87.67
Number of reversals	141.80	162.70	14.74	69.30	74.20	7.07	124.40	170.30	36.90	179.10	201.10	12.28	148.00	160.00	8.11

DF (Deviation Factor) = ((Post-Pre)/Pre)*100; Pre=Reference impact period (Before dam construction); Post = Test impact period (After dam construction)

4.2.1 Group-1: Monthly streamflow

Monthly streamflow represents the intra-monthly variability for pre- and post-construction periods. In terms of environmental impact, it also provides a general measure of temporal variation of habitat availability or suitability. The similarity of the monthly mean streamflow within a year reflects the conditions of relative hydrologic constancy. HA value represents the shift in inflow from one month to another month.

Table 4.5 gives the HA values for the Krishna River at the five hydrological stations. Most of the mean monthly values of HA are higher. The most affected hydrological station is Vijayawada which shows high alteration for a period of 7 months, viz., June, August (0.98), September (0.72), and January to April. The HA values range between 0.02 and 0.66 for the other 5 months. This is because the NSP dam is the last dam in the study area, and Vijayawada is located downstream of NSP. The Yadgir station shows high alteration only for 4 months, namely, July (0.84), August (0.69), February (0.92) and March (0.76). In the case of Agraharam, the most affected months are June, September, October, February and April with HA values of 0.99, 0.76, 0.77, 0.98 and 0.94 respectively. For stations De Sugur and NSP, HA values for months of namely July, August, February, March, and April are high, which ranges from 0.67 to 0.99. Overall, a high degree of mean HA values were observed during the high flow season (i.e., June (0.73) – September (0.67)). This may be due to water being kept in storage by the dams in this season. In the case of October, HA values are moderate because the dams start to overflow after reaching the storage capacity. The mean HA value is low during the months of November (0.31) and December (0.33) due to the release of water from the dams. In the month of January (0.59), HA value is altered moderately, because water flow decreased slowly from the dam. The mean HA value is high in the month of February (0.83) to April (0.81) because no flow is released from the dams in this period, and HA value is moderate in the month of May (0.37) because hydropower operations take place at the dams in this period. Out of 12 months, flows in 7 months have altered highly; flows in 3 months have altered in moderate condition and remaining 2 months in low condition. Analyses show that moderate alteration was observed at Yadgir, Agraharam and De Sugur with mean yearly HA values of 0.51, 0.60 and 0.60 respectively. The high alteration was observed for NSP and Vijayawada stations with mean yearly HA values of 0.68 and 0.67 respectively.

4.2.2 Group-2: Magnitude and duration of annual extreme conditions

From the Table 4.5, it can be observed that mean HA value of most of the Group-2 events have altered moderately, which indicates that the monthly, weekly, daily minimum and maximum flow events are moderately influenced by the reservoir operations. At Yadgir and Vijayawada, minimum flow parameters are highly affected. 1-, 3-, and 7-day minimum flows of Agraharam have changed severely with HA value of 0.99. For NSP station, the seasonal minimum flows are highly affected, with HA value of 0.92. For De Sugur, monthly and seasonal low flows have high alteration with HA value of 0.73 and 0.80 respectively. When maximum flow events are considered, seasonal maximum flow is affected at Yadgir and De Sugur with HA value of 0.76 and 0.93 respectively. Monthly flow is affected at De Sugur and NSP with HA value of 0.87 and 0.75 respectively. HA values of 0.73 and 0.67 are observed for 90-days minimum and maximum flows considering the entire study area. These values indicate that quarterly low flow and seasonal cycles are highly affected. All the remaining group-2 parameters are altered moderately, the HA values ranging from 0.37 (3-day maximum) to 0.65 (30-day minimum).

High alteration in the base flow indices are observed at Yadgir, Agraharam and Vijayawada stations with HA values of 0.69, 0.76 and 0.89 respectively. This indicates that possible discharge volume has decreased in Krishna River. The results suggested that large environmental stress and disturbance occurred in the Krishna River basin.

4.2.3 Group-3: Timing of annual extreme water conditions

From Table 4.5, it can be seen that the timing of occurrence of the annual 1–day minimum flow has shifted forward at De Sugur and Vijayawada with mean HA values 0.87 and 0.77 respectively. Average HA value for 1-day maximum flow for the whole study area is 0.16 which showed low alteration in the occurrence of 1-day maximum flow.

4.2.4 Group-4: Frequency and duration of high and low pulses

The frequency parameters describe how regularly a flow regime magnitude occur over a specified time interval. The duration parameters describe the period of time a specific flow condition exists. It is observed that the frequency of low pulse count altered highly at Agraharam, De Sugur and Vijayawada stations with HA values of 0.76, 0.80 and 0.72 respectively (Table 4.5). The low pulse duration altered moderately at all stations, the HA values ranging from 0.33 (De Sugur) to 0.52 (Agraharam). High pulse duration has altered from low to moderate at all stations with HA values varying from 0.04 (Agraharam) to 0.52 (De Sugur). This is because of the rapidly shrinking storage capacity of the reservoir.

4.2.5 Group-5: Rate and frequency of water condition changes

Rise rate HA value of Yadgir (0.84) and Vijayawada (0.83) stations are highly altered, and at the remaining stations, the alteration is low. The fall rate HA value at Vijayawada (0.77) station is high. The same parameter shows low alteration at De Sugur (0.20) and Yadgir (0.18) stations, while the HA values of Agraharam (0.45) and NSP (0.50) are in moderate condition. The mean rise rate and fall rate HA value at all stations are 0.51 and 0.42 respectively.

Table 4.5 Measures of Hydrologic Alteration (HA) at five hydrological stations

IHA Factor	Stations						Range
	De Sugur	Yadgir	Agraharam	NSP	Vijayawada	Average	
June	**0.99**	0.45	**0.94**	0.58	**0.89**	**0.77**	H
July	**0.87**	**0.84**	0.52	**0.92**	0.49	**0.73**	H
August	**0.67**	**0.69**	0.52	**0.92**	**0.98**	**0.76**	H
September	0.53	0.45	**0.99**	0.66	**0.72**	**0.67**	H
October	0.20	0.10	**0.76**	0.50	0.44	0.40	M
November	0.53	0.29	0.52	0.17	0.02	0.31	L
December	0.13	0.22	0.21	0.41	0.66	0.33	L
January	0.60	0.61	0.03	0.92	**0.77**	0.59	M
February	**0.80**	**0.92**	**0.77**	**0.92**	**0.77**	**0.83**	H
March	**0.87**	**0.76**	0.52	**0.92**	**0.97**	**0.81**	H
April	**0.80**	0.53	**0.98**	**0.83**	**0.89**	**0.81**	H
May	0.20	0.37	0.52	0.16	0.61	0.37	M
1-day min	0.00	**0.76**	**1.00**	0.03	**0.94**	0.55	M
3-day min	0.07	**0.76**	**1.00**	0.20	**0.94**	0.60	M
7-day min	0.13	**0.69**	**1.00**	0.26	**0.94**	0.60	M
30-day min	**0.73**	**0.84**	0.52	0.25	**0.89**	0.65	M
90-day min	**0.80**	**0.76**	0.27	**0.92**	**0.89**	**0.73**	H
1-day max	**0.67**	0.53	0.03	0.08	0.21	0.30	L
3-day max	0.53	0.61	0.27	0.25	0.21	0.37	M
7-day max	0.40	0.45	0.27	0.58	0.27	0.39	M
30-day max	**0.87**	0.29	0.52	**0.75**	0.49	0.58	M
90-day max	**0.93**	**0.76**	0.52	0.50	0.61	**0.67**	H
Number of zero days	0.00	0.22	0.09	**0.75**	0.06	0.22	L
Base flow index	0.60	**0.69**	**0.76**	0.16	**0.89**	0.62	M
Date of min	**0.87**	0.53	0.03	0.33	**0.77**	0.51	M
Date of max	0.00	0.25	0.21	0.17	0.15	0.16	L
Low pulse count	**0.80**	0.18	**0.76**	0.58	**0.72**	0.61	M
Low pulse duration	0.33	0.44	0.52	0.34	0.44	0.41	M
High pulse count	0.52	0.32	0.04	0.31	0.20	0.28	L
High pulse duration	0.27	0.40	0.17	0.17	0.62	0.32	L
Rise rate	0.33	**0.84**	0.27	0.25	**0.83**	0.51	M
Fall rate	0.20	0.18	0.45	0.50	**0.77**	0.42	M

*Bold indicated high alteration (>0.67%)

4.3 Spatial Patterns of HA

The HA values of the 33 parameters for five gauging stations were investigated to study the hydrological alterations caused by the dams. It is not necessary to determine the degree of hydrological alteration for all the 33 parameters. The average value of each parameter for 5 stations is chosen as an indicator. The top 67 percentile among the 33 indicators are considered as the most influencing indicators. Fig 4.1 presents the 33rd and 67th percentile values, which are obtained from the mean of 33 IHA parameters of the five stations. Then, the indicators with a mean value higher than the 67^{th} percentile value namely, February, March, April, August, September, 90-day minimum, 90-day maximum, 30-day minimum, Base flow index, and low pulse count were used for calculation of hydrological alterations that take place along the river. These 10 indicators were highly affected by the location as well as the operation of the dam across the river. For each station, the overall degrees of HA are calculated for these 10 selected parameters. From Table 4.6, it can be observed that the overall degree of HA for the five hydrological stations ranged from 59% to 81%, i.e., moderate to high alteration. The results indicated that the flow along the upper-lower reaches of the Krishna River were highly altered after the commissioning of the dams. The degree of HA varied with the distance away from the dam.

Table 4.6 Degree of hydrological alteration at the five gauging stations

Parameter	Station				
	De Sugur	Yadgir	Agraharam	NSP	Vijayawada
February	0.80	0.92	0.76	0.92	0.77
March	0.87	0.76	0.52	0.92	1.00
April	0.80	0.53	1.00	0.83	0.89
August	0.67	0.69	0.52	0.92	1.00
90-day minimum	0.80	0.76	0.27	0.92	0.89
September	0.53	0.45	1.00	0.67	0.72
90-day maximum	0.93	0.76	0.52	0.50	0.61
30-day minimum	0.73	0.84	0.52	0.25	0.89
Base flow index	0.60	0.69	0.76	0.16	0.89
Low pulse count	0.80	0.18	0.76	0.58	0.72
Average	0.75	0.66	0.59	0.67	0.81
Condition	H	M	M	H	H

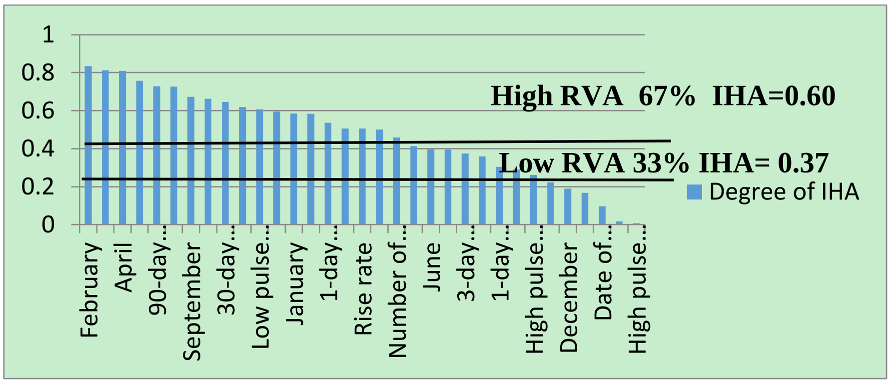


Fig.4.2 Percentile values of 33 IHA parameters arranged in ranking for the middle category

4.4 Possible Impacts due to the Absence of Natural Flow

In the Krishna River, there were many flood events in the past causing the water during the rainy season spread all over the basin. But, due to the construction of the dams in the upper reaches along the river, the downstream sections of the river became a non-flooding dry river reach and the wetlands look like a sandy beach. Moreover, because of no release of water from the dams, some sections of the river downstream have become like a drain. Due to the construction of the dams, the groundwater level continued to decline, and the land on both sides of the river are eroded (Zende and Nagarajan, 2012). Continuing anthropogenic activities in the basin cause the water in the basin to be polluted and the ecological environment gets deteriorated. The pollution of the ecological environment not only affects the safety of rural drinking water but also leads to a reduction of large-scale cultivated land in the river basins. The vegetation that depend on periodic floods are unable to grow and sustain during certain periods due to inadequate soil moisture during the seed germination time, resulting in continuous degradation of vegetation and trees that have become sparse. The human activities altered the upper and lower water bodies in the river basin and blocked the natural corridors of biological movements in the river basins. The anthropogenic activities also affect the biodiversity by reducing the number of aquatic animals in the river basin. The number of bird species which are depending on these habitats in the basin are reduced which results in reduction of organisms. Due to the water storage in the upper reaches of the river, following changes were observed:

i. The river temperature and chemical composition of the river waters changed.

ii. The grasslands and forest lands are degraded, and the vegetation distribution area reduced.

iii. It cuts off the links between the ecological networks and results in degraded biodiversity.

4.5 Conclusions

The hydrologic analyses indicated that changes had occurred in the hydrology of the Krishna River during the post impact period after 1984, when compared to the pre-impact period of 1960 – 1984. The following conclusions can be drawn from the hydrologic analyses:

- The mean monthly streamflow had decreased from June to December and had increased from January to May along the basin.
- The largest positive relative increasing trend was observed in the low flow months of February, March, April, and May.
- The occurrence of high flows during the low flow season adversely affect the ecology of the river, especially those species that are seasonally adapted.
- Decreasing high flows were observed along the basin. Decreasing river flow affects the flushing property and increases the sedimentation deposit in one place.
- The frequency and magnitude of extreme events changed significantly at the NSP and Vijayawada station. The duration of the extreme events had changed so that the river was in low flow mode for a longer period than it was in the earlier period and the high flows do not flow for a period as long as it was in the early period.
- It was observed that in the Krishna River, average low and high flow occurrence shifted forward by 24 and 17 days respectively.
- Low and high pulse count showed an increase of 27% and 9% respectively along the basin.
- The low and high pulse counts decreased along the basin by 47% and 30% respectively. This type of changes can create dehydration stress and drought stress on plants on low-mobility stream edge organisms.
- The gauge stations at De Sugur, NSP and Vijayawada experienced very little change in the timing of extreme events. The number of high flow periods and duration of high flow pulses had decreased compared to the previous period representing that the river has less floods.

CHAPTER 5

ENVIRONMENTAL FLOW ASSESSMENT

5.1 Introduction

Based on the analysis carried out using the IHA tools, it is seen that Krishna River has lost her normal characteristics at upstream and downstream of the river due to the construction of dams. In the previous section, it is seen how the hydrological alteration has taken place in the Krishna River due to the anthropological activities. This analyses reveal that EF assessment for the sustainable development of the Krishna River is very essential.

While estimating the EF, various streamflow characteristics should be considered for the regeneration and maintenance of biological diversity and riverine habitats. These include the timing of extreme conditions, seasonal patterning of flows, predictability and duration of floods, the frequency, irregular daily flow and droughts, annual flow variability and seasonal. Streamflow is a useful indicator for evaluating the river ecosystem truthfully over time period, for several reasons. Many abiotic characteristics of riverine ecosystems vary with streamflow conditions, including water temperature, dissolved oxygen levels, etc. Secondly, on a larger scale, flood plain morphology and channel is shaped by fluvial processes driven by streamflow, mainly high-flow conditions. So, recommending and maintaining EF is necessary in rivers. Environmental flows are not just for providing single flow or low flows. Some of the most important functions of environmental flows require periodic high flows. Maintaining only low flows without consideration of the wider range and timing of the flows is not sufficient for the maintenance of the health of the river ecosystems and their services. Understanding the environmental flows of a river require recognising the key components of the flow regime and their roles in maintaining healthy ecosystems. Provision of the environmental flow follows the natural flow pattern to enable the ecosystem processes function throughout the year (Walther, 2016). For this study, the daily time series of discharge measured at stations downstream before construction of dams have been used to calculate EF. The environmental flow values estimated by using the two methods (i.e., DRM and GEFC) and non-attainment calculation of dams constructed upstream and downstream have been analysed for two-time steps: before construction of dams and after the construction of the dams. Detailed analysis and results are described in this section.

5.2 Tennant Method

Analyses of the data carried out with pre-period show different scenarios for different conditions as stated by Tennant (1976). The mean annual flows are found to be 367m^3/s, 647m^3/s, 851m^3/s, 1306m^3/s and 1273m^3/s at De Sugur, Yadgir, Agraharam, NSP and Vijayawada stations respectively. In the Krishna River, five months (January to May) are considered as dry months, among which April is the driest month; rest of the seven months are considered as wet months. Therefore, flows in January to May in the river are highly vulnerable for its ecosystem according to Tennant. As per Tennant's recommendation, in order to maintain a stream in good condition, more than 30% and 40% of MAF should be available during the months of January to May and June to December respectively. Same percentage values are used in this study and given in Table 5.1. According to Tennant, flow below 10% of MAF is not acceptable. This method has severe limitations and should be restricted to reconnaissance level planning (Poff et al., 2017). In this research, the results obtained from this method are used to compare the river's ecological status with that obtained from the other methods.

Table 5.1 Recommended EF using Tennant Method (All values in m^3/s)

Months	Dams				
	Narayanapur	Ujjani	PD Jurala	Srisailam	Nagarjuna Sagar
January	12.00	13.50	17.56	48.25	48.32
February	13.91	8.10	15.04	36.58	36.65
March	9.79	4.50	12.39	27.28	27.33
April	3.45	2.10	8.47	24.94	24.94
May	8.20	4.50	7.90	25.85	25.81
June	153.20	55.20	159.26	192.13	196.46
July	914.00	190.80	1061.04	1122.80	1077.24
August	1246.40	335.70	1458.76	1977.68	1912.45
September	511.60	331.50	877.73	1361.72	1354.46
October	173.24	286.50	563.53	1013.14	981.21
November	39.14	76.50	87.56	210.18	274.42
December	19.36	30.00	27.11	78.88	101.24

5.2 Analysis using DRM Method

The environmental flow requirements were calculated for all the stations for categories A to D with DRM approach. As per DRM, the magnitude of the environmental flow increases with the increasing Base Flow Index (BFI). The BFI varies from 0.47 to 0.49 in the Krishna River. The DRM presents the environmental flow requirements required for the specified class, in volume/year. EFRs with annual average runoff for each class from A to D are varying from

58.61 % to 15.55 % for De Sugur station, 52.43 % to 14.86 % for Yadgir station, 52.76% to 14.91 % for Agraharam station, 53.22 % to 14.96 % for NSP station and 52.47 % to 13.87 % for Vijayawada station. It is observed that the difference between the lowest EFR (lowest percentage of the natural flow) and the highest EFR (highest percentage of the natural flow) in a particular class is slightly lower for the lower class (Class D) than for the higher class (Class A). The average variance among the demanded EFR as percentage of MAF for class A and class B is 9.50 % (taken as all station average). The difference between A and B is 8.91 %, between B and C is 6.07 % and between C and D is 6.44 %. Another observed difference is that the EFR distribution is larger for a higher class than that for a lower class. For example, the difference between the maximum EFR for a class A and the minimum EFR for a class A is 5.16 %, while, the difference for a class C is only 1.11 %.

DRM estimated water necessities for four classes. Hence, the results of class B have been taken up for the study in order to manage both the human demands as well as environmental requirements. The total environmental flow maintenance at each station is calculated as the sum of the low flow maintenance and high flow maintenance. Table 5.2 shows the calculated total maintenance flow at De Sugur station, i.e., 2,978 m^3/s, which must be released from the PD Jurala dam to preserve the river in class "B" condition according to DRM method. Table 5.3 shows the DRM results for Yadgir station, which show that 1,559 m^3/s total flow should be released from the Ujjani dam to maintain the river in class "B". From Table 5.4, results of the analysis at Agraharam station suggest that minimum total EF that should be released from the PD Jurala dam is 3,591 m^3/s. It is seen that from Table 5.5, that in order to preserve the river in Class “B”, an average annual environmental flow allocation of 5,542 m^3/s is needed under Srisailam dam and should be released from the dam. The flow calculated at Vijayawada station is 5,441 m^3/s which should be released from the NSP dam to maintain the downstream of the river in class “C” (Table 5.6). Estimated monthly long-term EFR of natural flow for class “B” for the five dams are presented in Table 5.2 to Table 5.6. The drought-low-flow corresponds to 9.07 %, 6 %, 7.63%, 7.74 % and 7.73 % for Narayanapur, Ujjani, PD Jurala, Srisailam, and Nagarjuna Sagar dams respectively. Drought flow indicates the minimum flow that should be released from the dams under any condition.

Table 5.2 The summary output from the DRM applied to the Krishna River at the De Sugur station for Ecological Category B

Narayanapur Dam				
BFI Index = 0.47		Total Flow = 38% MAF		
CV(*JAS+*MAM) Index = 1.26		Maintenance Low Flow= 28.95% MAF		
		Drought Low Flow = 9.07% MAF		
		Maintenance High Flow = 9.00% MAF		
Environmental Flow Requirement (m^3/sec)				
Month	Low Flows		High Flow (m^3/sec)	Total Maintenance EFR (m^3/sec)
	Maintenance (m^3/sec)	Drought (m^3/sec)		
January	19.30	6.26	0.47	19.78
February	19.38	6.29	1.77	21.15
March	12.71	4.21	1.28	14.00
April	3.67	1.39	0.00	3.67
May	6.41	2.00	0.00	6.41
June	81.69	25.69	0.00	81.69
July	495.34	154.54	52.85	548.15
August	762.18	237.67	490.77	1252.95
September	494.96	154.43	52.81	547.72
October	262.46	82.00	105.63	368.09
November	78.45	24.68	0.00	78.45
December	36.29	11.55	0.28	36.58

*JAS – July, August and September   * MAM – March, April and May
MCM – Million Cubic Meters   MAF – Mean Annual Flow

Table 5.3 The summary output from the DRM applied to the Krishna River at the Yadgir station, for Ecological Category B

Ujjani Dam				
BFI Index = 0.47		Total Flow = 35% MAF		
CV(*JAS+*MAM) Index = 1.81		Maintenance Low Flow= 25% MAF		
		Drought Low Flow = 6%MAF		
		Maintenance High Flow = 10.14% MAF		
Environmental Flow Requirement (m^3/sec)				
Month	Low Flows		High Flow (m^3/sec)	Total Maintenance EFR (m^3/sec)
	Maintenance (m^3/sec)	Drought (m^3/sec)		
January	20.97	1.00	0.21	21.18
February	11.88	0.00	0.07	11.96
March	5.73	0.00	0.09	5.83
April	1.86	0.00	0.00	1.86
May	2.51	0.00	0.00	2.51
June	33.02	7.00	0.00	33.03
July	119.22	36.17	48.92	168.18
August	226.22	68.52	251.39	477.61
September	260.00	78.75	48.92	308.92
October	254.29	34.00	97.85	352.15
November	124.63	37.80	3.15	127.79
December	46.97	5.00	1.58	48.55

*JAS – July, August and September
*MAM – March, April and May
MCM – Million Cubic Meters
MAF – Mean Annual Flow

Table 5.4 The summary output from the DRM applied to the Krishna River at the Agraharam station, for Ecological Category B

PD Jurala				
BFI Index = 0.47		Total Flow = 35 % MAF		
CV(*JAS+*MAM) Index = 1.76		Maintenance Low Flow= 25.07% MAF		
		Drought Low Flow = 7.63 % MAF		
		Maintenance High Flow = 10.07 % MAF		
Environmental Flow Requirement (m^3/sec)				
Month	Low Flows		High Flow (m^3/sec)	Total Maintenance EFR (m^3/sec)
	Maintenance (m^3/sec)	Drought (m^3/sec)		
January	25.45	8.09	0.73	26.19
February	19.78	6.38	0.92	20.71
March	15.36	5.04	0.67	16.03
April	9.07	3.13	0.00	9.07
May	5.92	2.00	0.00	5.92
June	69.14	21.32	0.00	69.14
July	465.09	141.09	92.83	557.88
August	721.53	218.69	653.06	1374.59
September	582.92	176.75	92.83	675.75
October	469.76	142.52	185.66	655.43
November	137.50	41.99	2.01	139.51
December	40.90	12.76	0.00	40.90

*JAS – July, August and September *MAM – March, April and May
MCM – Million Cubic Meters MAF – Mean Annual Flow

Table 5.5 The summary output from the DRM applied to the Krishna River at the Nagarjuna Sagar dam, for Ecological Category B

Srisailam Dam				
BFI Index = 0.49		Total EF = 35.36 % MAF		
CV(JAS+*MAM) Index = 1.70		Maintenance Low Flow = 25.39 % MAF		
		Drought Low Flow = 7.74 % MAF		
		Maintenance High Flow = 9.96 % MAF		
Environmental Flow Requirement (m^3/sec)				
Month	Low Flows		High Flow (m^3/sec)	Total Maintenance EFR (m^3/sec)
	Maintenance (m^3/sec)	Drought (m^3/sec)		
January	66.64	21.26	2.16	68.81
February	48.32	15.72	1.18	49.50
March	32.94	11.08	0.70	33.65
April	25.13	8.72	0.00	25.13
May	17.18	2.00	0.00	17.18
June	90.01	28.31	0.00	90.01
July	526.65	160.12	141.42	668.07
August	1011.02	306.34	979.54	1990.57
September	896.91	271.89	141.42	1038.33
October	807.90	245.02	282.84	1090.75
November	335.22	102.33	10.49	345.72
December	122.73	38.19	1.84	124.57

*JAS – July, August and September *MAM – March, April and May
MCM – Million Cubic Meters MAF – Mean Annual Flow

Table 5.6 The summary output from the DRM applied to the Krishna River at the Vijayawada station, for Ecological Category = B

Nagarjuna Sagar				
BFI Index = 0.48		Total EF = 36.25 % MAF		
CV(*JAS+*MAM) Index = 1.72		Maintenance Low Flow= 25.54 % MAF		
		Drought Low Flow = 7.73 % MAF		
		Maintenance High Flow = 10.04 % MAF		
Environmental Flow Requirement (m^3/sec)				
Month	Low Flows		High Flow	Total Maintenance EFR (m^3/sec)
	Maintenance	Drought		
	(m^3/sec)	(m^3/sec)	(m^3/sec)	
January	63.52	20.35	2.04	65.56
February	47.52	14.84	1.07	48.59
March	31.65	11.32	0.70	32.35
April	26.25	8.74	0.00	26.25
May	17.14	2.36	0.00	17.14
June	92.36	29.01	0.00	92.36
July	514.36	156.31	139.84	654.2
August	983.24	294.25	971.67	1954.91
September	884.21	268.54	138.14	1022.35
October	794.35	241.97	271.64	1065.99
November	331.52	97.74	9.87	341.39
December	119.59	37.67	1.69	121.28

*JAS – July, August and September *MAM – March, April and May
MCM – Million Cubic Meters MAF – Mean Annual Flow

5.3 Non-attainment Analysis

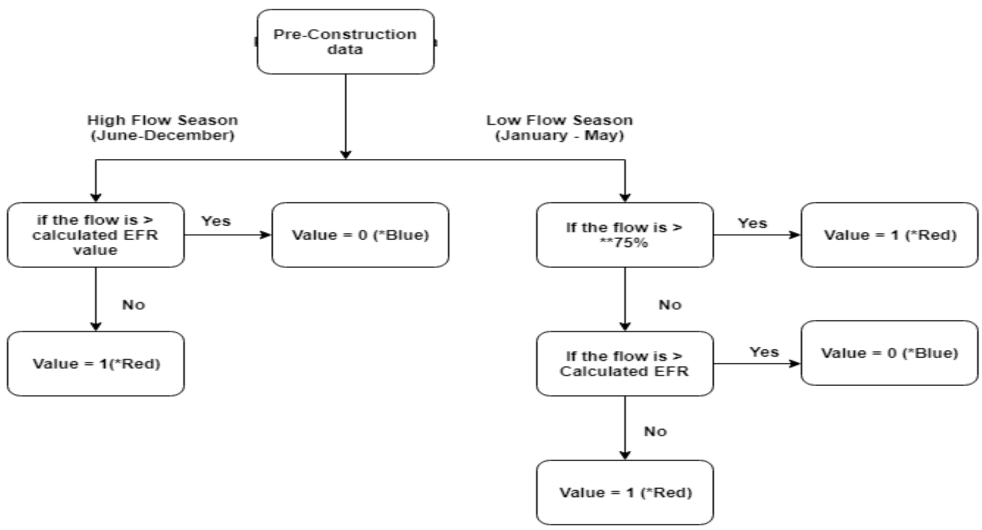
Non-attainment is used to analyse how the environmental flow requirements are different in post-period. Non-attainment explains that EF does not exceed or flow in the river during the required period. For example, if the data for a period of 46 years is taken (1965-2011), there will be 46 values for every month. Considering the month of March (46 values) for calculating the non-attainment flow, if the non-attainment value is found to be 35 %, it indicates that out of 46 months, during 35 % of total period (i.e., 16 months), the flow did not exceed or did not attain the EFR in a river. The calculation of Non-attainment is different for high flow season and low flow season. The complete calculation of Non-attainment is given in Fig 5.1.

5.3.1 Non-attainment for high and low flow season

During the post-impact period, if high flow season mean monthly flow value is less than the calculated EF value then that month can be called a non-attainment month. If mean monthly flow data is greater than the calculated EF value then the month can be called as attainment month. The cumulative total of non-attainment months is used to calculate the final Non-attainment (Eqn 5.1). This calculation is done for every month of the high flow season, i.e., June-December.

For low flow season two cases are considered to calculate non-attainment. In the first case, if monthly mean flow value is less than the calculated EF value then the month can be called a non-attainment month. In the second case, if the monthly mean flow value in the post period is greater than the 75th percentile in the per-period then the month also can be called as a non-attainment month. Because flow values above the 75th percentile occur mostly in the monsoon season only; if they occur in the non-monsoon season, it is a chance to damage the ecology. Finally, the cumulative of non-attainment months in both cases are considered in calculating the final non-attainment (Eqn 5.1). This calculation takes place every month of the low flow season, i.e., January-May.

$$\text{Non-attainment} = \frac{\text{Number of cumulative months}}{\text{Number of months in Post impact period}} * 100 \qquad (5.1)$$



****** The percentile values are fixed based on the Pre-impact period flow data

*Red=Non-attainment of EFR; *Blue= Attainment of EFR

Figure 5.1 Flow chart of non-attainment calculation

Monthly non-attainment flow analysis of DRM method is presented in Table 5.7. The results of the non-attainment analysis for EFRs calculated using DRM method are given in Fig. 5.2 to Fig. 5.6. It is necessary to investigate whether there is sufficient flow in the river or not. Hence, recorded monthly flows at each station for post-period were used to evaluate the flow attainment. The calculated monthly average EFR under DRM method is considered as a benchmark representing the natural flow, and these values are used to find the non-attainment flow for each month over the post-period. Analyses on the historic flow data showed a drastic flow reduction in the post-period, the results of which show an alarming situation to the agriculture as well as to the downstream users. From the Table 5.7, month-wise analysis, it can be observed that the non-attainment flow values ranged from 13.79% to 72.41%, 43.75% to 84.38%, 9.09 % to 45.45 %, 17.24% to 93.10%, and 17 % to 84.44 % at De Sugur, Yadgir, Agraharam, NSP and Vijayawada stations respectively. The overall average non-attainment rate for all throughout the post-period are obtained as 31.82 %, 36.49%, 52.04 %, 53.74 % and 65.63 % for Agraharam, De Sugur, Vijayawada, NSP, and Yadgir respectively. While the monthly average for the complete basin ranged from 34.57 % (December) to 61.62 % (April), the highest and lowest values were observed at Yadgir (65.54 %) and Agraharam (31.82 %) stations. Highly altered month and station are April (61.62%) and Yadgir (65.63%). It is evident from the results obtained that the variation of flow within the post-period for all stations is inconsistent. However, the flow is decreasing with time for all the seasons. It clearly indicates that the environmental flows in the river are not maintained in class B of DRM method for 46.92 % of the time in post-period, which indicates that the Krishna River is highly impacted. The high and low value was observed in the months of April (61.62 %) and June (48.08 %) and are due to hydropower activities and water storage in the dams.

In the Fig. 5.2 to Fig. 5.6, the red colour indicates non-attainment of EFR while the blue colour indicates the attainment of EFR. It can be noticed that at Agraharam station, low flow seasons have not attained EF from 1997 to 2000, when compared with high flow season. However, from 2001 to 2003 high flow seasons, environment flows are not attained while during the year 2004, in some months during the high flow season, EF is attained. In 2003, except May and December, all the other months have not attained EF. Moreover, from 2005 to 2007 changes are less, due to more floods in the upper reaches of the river. In the case of De Sugur station, the flow during April was altered highly for most of the years, and the remaining low flow months from 1985 to 2002 satisfied EFRs. Similarly from 2002 to 2011, the streamflow in the low flow seasons have altered highly in a positive way (i.e., flow are above

75%). During the high flow seasons, the EF are not met during the years from 1985 to 1989. Similarly, the streamflow in month of June changed significantly after 2000. If the results of NSP and Vijayawada stations are observed, the constant hydropower production in the upstream dams changed the flow regime during the low flow season and affected the downstream ecology. Red colour is observed from 1985 to 2013 in low flow season, and from 2001 to 2004, and 2011 to 2013 in high flow season.

Table 5.7 Fraction (%) of the EF not met in the Post-Impact years for DRM Method

Stations / Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
De Sugur	44.83	20.69	31.03	72.41	13.79	55.17	24.14	27.59	24.14	48.28	48.28	27.59	36.49
Yadgir	71.88	81.25	78.13	68.75	84.38	46.88	53.13	50.00	43.75	50.00	74.00	84.38	65.54
Agraharam	27.27	18.18	36.36	36.36	27.27	45.45	36.36	36.36	36.36	27.27	45.45	9.09	31.82
NSP	82.76	89.66	93.10	68.97	24.14	44.83	62.07	51.72	34.48	51.72	24.14	17.24	53.74
Vijayawada	80.00	82.22	84.44	66.67	22.22	44.44	62.22	53.33	33.33	51.11	26.67	17.78	52.04
Average	61.35	58.40	64.61	62.63	34.36	47.35	47.58	43.80	34.41	45.68	43.71	31.21	47.93

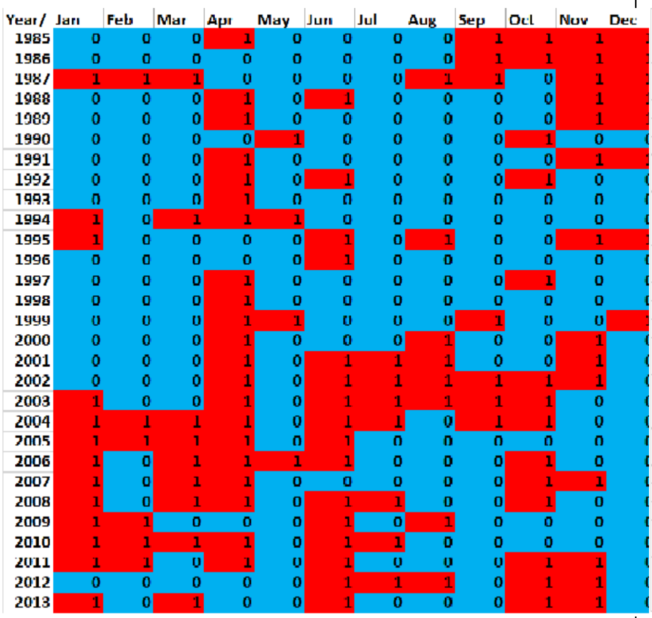


Fig.5.2 Monthly and yearly alterations by DRM method at De Sugur station

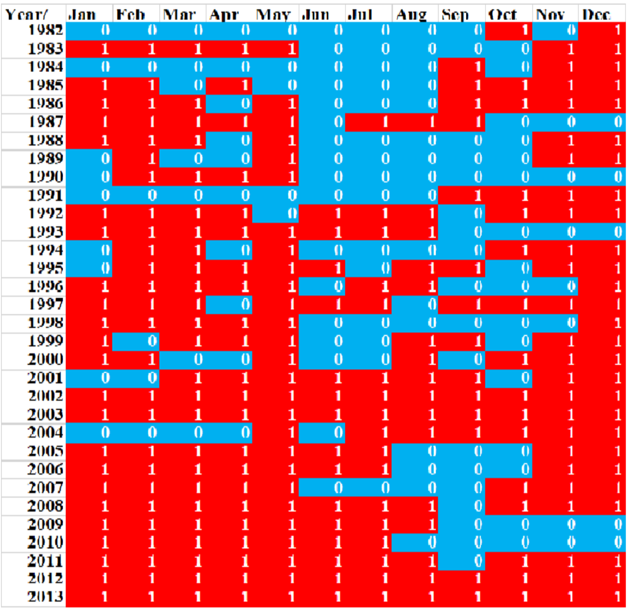


Fig.5.3 Monthly and yearly alterations by DRM method at Yadgir station

Year/ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	1	0	0	1	1	0	0	0	0	1	0	0
1998	0	1	0	1	0	0	0	0	0	0	0	0
1999	0	0	1	1	1	0	0	0	1	0	0	1
2000	0	0	1	0	0	0	0	1	0	0	1	0
2001	0	0	0	0	0	1	1	1	0	0	1	0
2002	1	0	0	0	0	1	1	1	1	1	1	0
2003	1	1	1	1	0	1	1	1	1	1	1	0
2004	0	0	0	0	1	0	1	0	1	0	1	0
2005	0	0	1	0	0	1	0	0	0	0	0	0
2006	0	0	0	0	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	1	0	0	0	0	0	0

Fig.5.4 Monthly and yearly alterations by DRM method at Agraharam station

Year/ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	1	1	1	1	1	0	0	0	1	1	0	0
1986	1	1	1	1	1	0	0	0	1	1	0	0
1987	1	1	1	0	1	0	1	1	1	1	0	0
1988	1	1	1	0	0	1	0	0	0	0	0	0
1989	1	1	1	0	0	1	0	1	0	0	0	0
1990	1	0	1	0	0	0	0	0	0	0	0	0
1991	1	1	1	0	0	0	0	0	0	1	0	0
1992	1	1	1	1	0	1	1	0	0	1	0	0
1993	1	1	1	1	0	0	0	0	0	0	0	0
1994	1	1	1	1	1	0	0	0	0	0	0	0
1995	1	1	1	1	0	1	1	1	1	1	0	0
1996	1	1	1	1	0	1	1	1	0	0	0	0
1997	1	1	1	1	0	1	1	0	0	1	1	0
1998	1	1	1	1	0	1	1	1	0	0	0	0
1999	1	1	1	1	0	0	0	0	1	0	0	0
2000	1	1	1	1	1	0	1	1	0	0	0	0
2001	1	1	1	0	0	1	1	1	1	0	1	0
2002	1	1	1	0	0	1	1	1	1	1	0	1
2003	0	0	0	1	1	1	1	1	1	1	0	0
2004	0	0	0	1	0	1	1	1	1	1	0	0
2005	0	1	1	0	0	0	1	0	0	0	0	0
2006	1	1	1	1	0	0	0	0	0	0	0	0
2007	0	1	1	1	0	0	0	0	0	1	1	0
2008	1	1	1	1	1	0	1	1	0	1	1	1
2009	1	1	1	0	0	0	1	1	0	0	0	0
2010	1	1	1	1	0	1	1	0	0	0	0	0
2011	0	1	1	1	0	0	1	1	0	1	1	1
2012	1	1	1	1	0	1	1	1	1	1	1	1
2013	1	1	1	1	0	0	1	1	1	1	1	1

Fig.5.5 Monthly and yearly alterations by DRM method at NSP station

Year/ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1970	0	1	1	1	1	0	1	0	1	1	0	1
1971	1	1	1	1	1	0	1	0	0	1	0	0
1972	1	0	1	1	1	0	1	0	1	1	0	0
1973	1	1	1	0	0	1	0	1	0	1	0	0
1974	1	1	1	0	0	1	0	1	0	0	0	0
1975	1	0	1	0	0	0	0	0	0	0	0	0
1976	0	1	1	1	0	1	0	1	0	1	0	0
1977	1	0	1	1	0	1	1	0	0	1	0	0
1978	1	1	1	1	0	1	0	0	0	0	0	0
1979	1	1	1	0	0	0	1	0	1	0	0	0
1980	1	0	1	1	0	0	1	1	1	1	1	0
1981	1	0	1	1	0	1	1	1	0	1	0	0
1982	1	1	1	0	1	0	1	0	0	1	0	0
1983	1	1	1	1	0	1	1	1	0	0	1	0
1984	1	1	1	1	0	0	1	0	1	0	0	0
1985	1	1	1	1	0	0	1	1	0	0	0	0
1986	1	1	1	0	0	1	1	0	1	0	1	1
1987	1	1	1	1	0	1	1	1	1	1	0	0
1988	1	1	0	1	1	1	0	1	0	0	0	0
1989	0	0	1	1	0	1	1	0	1	1	0	0
1990	1	1	0	0	0	0	1	1	0	1	0	0
1991	1	1	1	1	0	0	0	0	0	0	1	0
1992	0	1	0	1	0	1	0	1	0	1	1	0
1993	1	1	1	1	1	0	1	1	0	1	1	0
1994	1	0	1	0	1	0	1	1	1	0	0	1
1995	1	1	1	1	0	0	0	0	0	0	0	0
1996	0	1	1	1	0	0	1	1	0	1	0	1
1997	1	1	1	0	0	1	1	1	0	0	1	0
1998	1	1	1	1	0	0	0	0	1	1	1	1
1999	1	1	0	1	0	1	1	1	0	0	0	0
2000	1	1	1	1	0	1	0	0	1	0	0	0
2001	1	1	1	1	1	0	1	1	0	0	0	0
2002	1	1	1	0	0	1	0	1	0	0	1	0
2003	1	1	1	0	0	0	1	0	1	1	0	1
2004	1	1	0	1	0	0	0	0	0	0	0	0
2005	0	0	0	1	0	1	1	1	1	1	0	0
2006	1	1	1	0	1	0	1	0	0	1	0	0
2007	1	1	1	0	0	1	0	0	1	0	0	0
2008	0	1	1	1	0	0	0	0	0	1	1	0
2009	1	1	1	1	0	0	1	1	0	0	0	1
2010	1	1	1	0	0	0	0	1	0	0	0	0
2011	1	1	0	1	0	1	1	0	0	1	0	0
2012	0	1	1	0	1	0	1	1	0	0	1	0
2013	1	1	1	1	0	1	1	1	0	1	1	0
2014	0	1	1	1	0	0	0	1	1	1	0	1

Fig.5.6 Monthly and yearly alterations by DRM method at Vijayawada station

5.4 Analysis using GEFC Method

The potential environmental flow values for the Krishna River were evaluated by GEFC. Monthly flow data at five gauging stations along the Krishna River was used to develop "Flow Duration Curve" (FDC) and to generate environmental flow requirements corresponding to different levels of EMCs namely, A, B, C, D, E, and F which refer to unmodified natural condition (Class A) to critically modified condition (Class F). FDCs corresponding to six different EMCs at five stations in Krishna River using probability distribution of discharges at seventeen fixed points are shown in the Fig. 5.7 to Fig. 5.11 for the selected stations. It is seen from the Fig. 5.7 to Fig. 5.11 that the natural flow in NSP was the highest among the five stations, reaching up to 40,630 MCM, followed by Agraharam (26,584 MCM), De Sugur (21,073 MCM) and Yadgir (11,374 MCM). According to FDC, probability of highest flow was 0.01% for all EMCs with different flows which varied from EMC-A to EMC-F. The lowest flow was available 99.99% of the time for all EMCs.

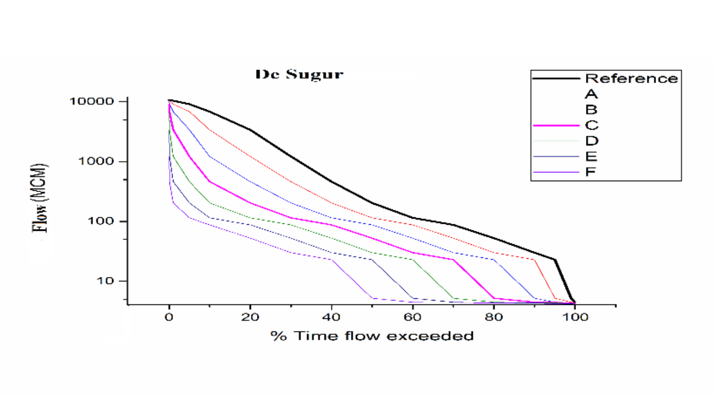


Fig.5.7 FDCs for different Environmental Management Classes at De Sugur by GEFC

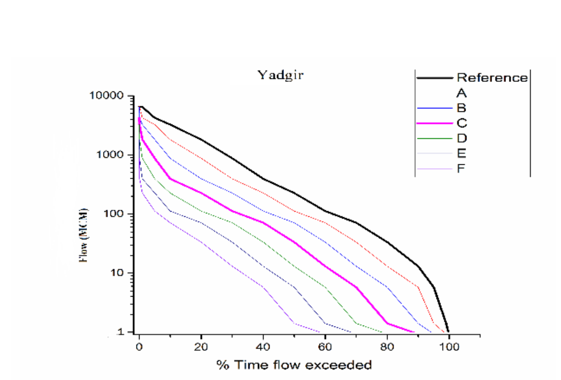


Fig.5.8 FDCs for different Environmental Management Classes at Yadgir by GEFC

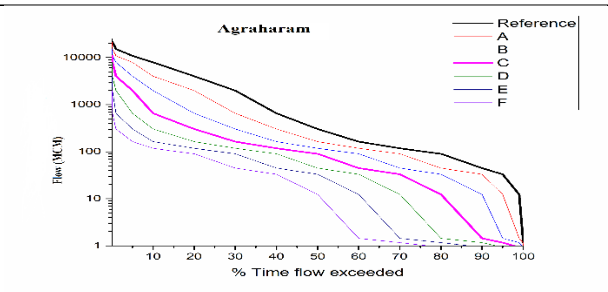


Fig.5.9 FDCs for different Environmental Management Classes at Agraharam by GEFC

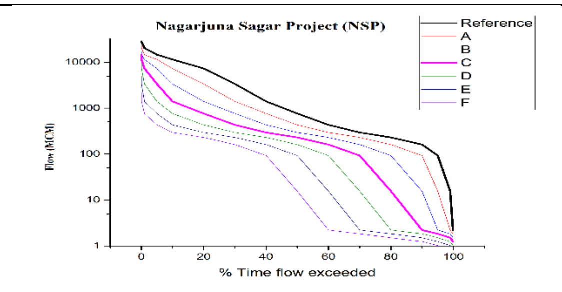


Fig.5.10 FDCs for different Environmental Management Classes at NSP by GEFC

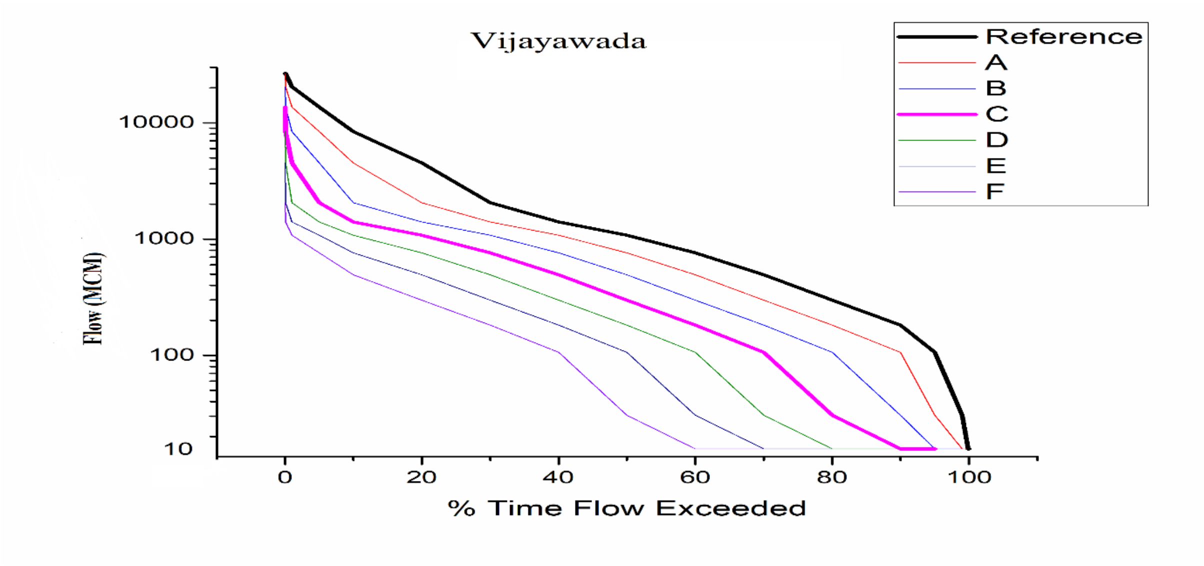


Fig.5.11 FDCs for different Environmental Management Classes at Vijayawada by GEFC

It is observed from the Table 5.8 that the EFR with annual average runoff for each EMC, for all classes from A to F, was varying from 59.2% to 1.8% at De Sugur, 70.5% to 2.5% at Yadgir, 68.4 % to 2 % at Agraharam, 72 % to 3.3 % at NSP and 71.31% to 3.2% at Vijayawada. It is evident from the Table 5.8 that class A requires more MAF as compared to other classes. As water allocation decreases, the protection of the ecosystem decreases. EMC A is not the right suggestion for Krishna River because this class is very near to natural flow which may create some hardship to the dam authorities for meeting water demand for hydropower generation and other uses. According to Tennant (1976), more than 10% of the MAF must be allocated to maintain the river life. If the flow is lower than this value, the river would be considered to be in a dead environment. Therefore, if EMCs D, E, and F are adopted, there will be a very low flow as suggested by the GEFC, and this low flow is inadequate for maintaining river water quality and aquatic life. Further, flow corresponding to EMCs B or C may be considered as a minimum flow for maintaining water quality and aquatic life at the downstream side of the Krishna River. Finally, the EMC C was chosen based on the ecological values of the river and the current water resources development projects. Estimated monthly long-term EF values at five stations are recommended to release from the five dams are presented in Table 5.9. Monthly EFRs hydrograph for class C was varying from 1.72 m^3/s to 866.29 m^3/s for Narayanapur dam, 2.43 m^3/s to 327.76 m^3/s for Ujjani dam, 9.98 m^3/s to 1,565 m^3/s for Srisailam dam, 16.18 m^3/s to 1,412.14 m^3/s for Nagarjuna Sagar. From the Table 5.9, it is observed that the average EFR calculated at De Sugur station for maintaining river in class

C is 177.69 m^3/s and this quantity should be released from Narayanapur dam. Results at Yadgir station suggested that 85.92 m^3/s of average environmental flow should be released from Ujjani dam to preserve the river in EMC-C. Agraharam station results show that 204.83 m^3/s of average EF should be released from the PD Jurala dam. From the Srisailam dam, average EF to be released is 345.58 m^3/s based on the NSP station results. Average EFR value calculated at Vijayawada station is 324.75 m^3/s and this flow should be released from the Nagarjuna Sagar to maintain the downstream in EMC - C.

Table 5.8 Environmental Management Classes of five station of Krishna River in percentages of MAF

Class	De Sugur	Yadgir	Agraharam	NSP	Vijayawada
A	69.20	70.54	68.49	72.04	71.31
B	41.21	44.33	41.54	46.26	45.24
C	24.72	26.41	24.12	27.5.42	26.64
D	6.66	9.21	7.44	10.30	9.67
E	3.26	4.75	3.65	5.61	5.44
F	1.85	2.56	2.01	3.34	3.25

Table 5.9 Estimated EFR for various sites in Krishna River basin with GEFC

Months	Flow to be released from Dams (m^3/s)				
	Narayanapur	Ujjani	PD Jurala	Srisailam	Nagarjuna Sagar
January	14.11	13.47	16.39	52.37	45.16
February	16.32	8.24	12.60	34.04	31.74
March	10.86	2.43	9.16	19.10	26.41
April	6.11	4.90	4.69	9.99	18.25
May	1.72	5.63	5.08	16.80	16.18
June	47.49	19.74	50.70	94.53	92.36
July	338.53	92.76	474.72	440.58	412.57
August	866.29	327.76	924.00	1565.08	1412.14
September	669.62	195.92	417.25	849.06	812.34
October	90.81	221.54	454.85	760.17	749.34
November	45.54	90.89	64.45	232.66	212.54
December	24.89	47.80	24.06	72.62	67.94
Average	177.69	85.92	204.83	345.58	324.75

Calculated monthly EFR are used to evaluate the post-impact period flow similar to that by the DRM method. Table 5.10 shows the non-attainment percentile of flow values obtained from GEFC. Considering the month-wise analysis, the non-attainment flow ranged from 5.46 % to 73.14 %, 40.65 % to 85.12 %, 6.76% to 42.65%, 13.94 % to 88.65 % and 12.64 % to 79.62 % at De Sugur, Yadgir, Agraharam, NSP and Vijayawada stations respectively.

The overall average non-attainment rate for all stations throughout the post-period was 29.24 %, 62.63 %, 27.61 %, 48.79 % and 47.13% for the five stations. While monthly average for complete basin ranged from 28.52% (December) to 60.25 % (March), the highest and lowest values were observed at Yadgir (62.64 %) and Agraharam (27.61 %). Non-attainment results by GEFC show that the river is not maintained in class “C” for 43% of time in post period, which indicated that the Krishna River was highly impacted. High and low value were observed in the months of March and December due to the hydropower activities and water available at the dam respectively.

Table 5.10 Fraction (%) of the EF not met in the Post-Impact period for GEFC Method

Station/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
De Sugur	23.14	16.32	26.34	73.14	5.46	35.14	16.14	21.67	26.57	39.64	42.67	24.65	29.24
Yadgir	68.24	78.65	75.68	69.98	85.12	44.36	41.65	44.69	40.65	46.39	71.65	84.65	62.64
Agraharam	21.65	15.64	30.98	33.97	27.12	42.65	34.69	22.64	29.64	23.65	41.95	6.76	27.61
NSP	78.65	85.64	88.65	54.36	24.01	45.32	52.32	45.67	31.64	43.64	21.64	13.94	48.79
Vijayawada	74.64	78.64	79.62	61.34	21.34	44.44	54.32	42.94	28.64	47.69	19.34	12.64	47.13
Average	53.26	54.97	60.25	58.55	32.61	42.38	39.82	35.52	31.42	40.20	39.45	28.52	43.08

5.5 Summary and Conclusion

In this study, The DRM and GEFC methods are used to estimate the EFR at five gauging station. The results of class “B” and class “C” for DRM and GEFC are used in the study in order to manage both the human demands as well as environmental requirements with reference to the Tennent method. The calculated EFRs under DRM and GEFC method are considered as the benchmarks representing the natural flow, and are used to find the flow non-attainment of each month over a post-period. The results of the non-attainment analysis indicate that the required environmental flows in the Krishna River are not maintained in class B of DRM method and class C of GEFC method with non-attainment values of 46.92% and 43 % of the time in post-period. Hence, studies for planning of EFR in Krishna River is highly necessary. This study evaluated the EFR by using only hydrological data of the Krishna River. However, the changes in ecological studies owing to the river basin characteristic change (e.g. land use change, land cover change, water quality, etc.) can also be used in the study and it would be potential for future work.

CHAPTER 6

FLOW HEALTH ANALYSIS

6.1 Introduction

Flow Health (FH) methodology was developed by adopting the nine most important ecological indicators of river flow regime. The FH analysis is carried out by comparing the flow data before and after construction periods of the dam in a river to calculate the alteration rate in the form of a FH score for the ecological indicators. Based on the FH scores for the nine ecological indicators identified, environmental flow magnitudes are calculated to develop action plans to preserve the ecological integrity of the Krishna River. The main purpose of introducing FH method is to calculate EFR based on the nine ecological indicators. The advantage of FH methodology is that one can see how much alteration can be reduced by considering the calculated EF, while the other two methods, viz., DRM and GEFC are not able to describe about it. The nine indicators are High flow (HF), Highest monthly (HM) flow, Low flow (LF), Lowest monthly (LM) flow, Persistently higher Flow (PH), Persistently lower flow (PL), Persistently very low flow (PVL), Seasonality flow shift (SFS) and Flood flow interval (FFI), and their descriptions are already available in Section 3.4. Discussion of these indicators are provided in the following sections and the results are presented in Table 6.1. In this chapter, the pre-impact period refers to a reference period and the post-impact period refers to a test period.

6.2 High Flow (HF)

In all the five stations, the flow health scores of high flow (HF) in the test period show comparatively lesser values than that obtained in the reference period. The HF scores for all stations in test period range from 0.24 to 0.40, which are lower than that were obtained in the reference period, which ranged from 0.82 to 0.85, indicating that high flow months are strongly influenced by the fluctuations in reservoir operations in the test period. FH scores of HF at NSP and Vijayawada stations were obtained as 0.82 and 0.85 respectively in the reference period and 0.24 and 0.34 respectively in the test period, as seen from Table 6.1. This large alteration is mainly attributed to the obstruction caused by dams during the high flow seasons. FH score of HF at Vijayawada was highly altered after 1999, most of which were having FH score less than 0.3 (large alteration) resulting in a long-term average FH score as 0.24. In addition, the

FH scores of HF at NSP, Agraharam, De Sugur, and Yadgir stations were altered to 0.34, 0.37, 0.30 and 0.40 respectively. The overall mean scores of five stations decreased by 60%.

Table 6.1 Comparison of results of Flow Health scores under five dams along the Krishna River

Indicator	**De Sugur**		**Agraharam**		**Yadgir**		**NSP**		**Vijayawada**		**Mean**	
	Ref	**Test**	**Ref**	**Test**	**Ref**	**Test**	**Ref**	**Test**	**Ref**	**Test**	**Ref**	**Test**
High flow (HF)	0.83	0.30	0.84	0.37	0.84	0.40	0.85	0.34	0.82	0.24	0.84	0.33
Highest monthly (HM)	0.83	0.30	0.84	0.47	0.84	0.46	0.85	0.39	0.81	0.38	0.83	0.40
Low flow (LF)	0.80	0.88	0.80	0.79	0.81	0.58	0.81	0.76	0.86	0.74	0.81	0.75
Lowest monthly (LM)	0.80	0.82	0.80	0.82	0.80	0.57	0.81	0.81	0.84	0.84	0.81	0.77
Persistently higher (PH)	0.79	0.59	0.82	0.54	0.78	0.59	0.85	0.30	0.88	0.31	0.82	0.47
Persistently lower (PL)	0.82	0.63	0.83	0.72	0.84	0.56	0.80	0.76	0.86	0.64	0.83	0.66
Persistently very low (PVL)	0.96	0.94	0.97	0.98	0.97	0.99	0.97	0.95	0.98	0.94	0.97	0.96
Seasonality flow shift (SFS)	0.76	0.40	0.79	0.36	0.80	0.47	0.78	0.07	0.74	0.1	0.77	0.28
Flood flow interval (FFI)	1	0.77	0.97	0.88	0.97	0.76	0.92	0.71	0.94	0.69	0.96	0.76
Flow health score (FH)	0.84	0.62	0.85	0.65	0.85	0.59	0.85	0.56	0.86	0.54	0.85	0.59

6.3 Highest Monthly Flow (HM)

The mean FH score of HM decreased from 0.83 (very small impact) in the reference period to 0.40 (large impact) in the test period. The scores of HM for all stations in the test period ranged from 0.30 to 0.47 which were less than that of the reference period, which ranged from 0.81 to 0.85. This indicates that large floods totally disappeared and small floods were decreased in terms of magnitude and occurrence. Large alterations were observed at De Sugur, NSP and Vijayawada stations with FH scores of 0.30, 0.39 and 0.38 respectively. Moderate alterations were observed at Agraharam and Yadgir stations with FH scores of 0.47 and 0.46 respectively. In the case of NSP and Vijayawada stations, flow health scores of HM is high because Srisailam and Nagarjuna Sagar dams are located in the lower basin. So most of the flood water gets collected on the upstream basin. Due to this, major useful ions travelling from upstream to downstream decrease and heavy metals deposit increases, which further leads to deterioration of the aquatic body (Acreman, 2016). In the reference impact period, the sediment along Srisailam and Nagarjuna Sagar sections were basically transported from upstream runoff. Due to the construction of reservoirs on the upstream, the sediment load on the downstream side decreased. The sedimentation in the downstream river channel after the construction of a reservoir was mainly the silt that scoured off from the riverbed. Due to less sedimentation, the physical characteristics of the channel has changed as well as corresponding change in relationship between water level and river flow.

6.4 Low Flow (LF) and Lowest Monthly (LM) Flow

It is seen that there is about 8% variation in the mean score of FH for the LF indicator compared to the test and reference period (score change from 0.81 to 0.75). The FH score for LF at De Sugur changed positively, with the FH score varying from 0.80 to 0.88 in the reference and test impact periods respectively. The flows coming from the Narayanapur dam during 2000-2014 in low flow season was more flat with a relatively smaller volume and with fewer fluctuations. Flat flows are more favourable for those low flow-enduring aquatic plants and small fluctuation-appetite plants. But information regarding the water level fluctuation is also very important with regard to its impact on the function of the river ecosystem, especially in the growth and distribution of aquatic plants. Yadgir has the highest alteration among all the stations. FH scores for LF at Yadgir decreased by 28% from the reference impact period. Low alteration score values were observed in remaining stations. It was due to the release of water for irrigation and hydropower during low flow season. Lowest monthly (LM) flow rate of Yadgir has FH scores of 0.57 and 0.80 during the test impact period and the reference period respectively, which indicate that more low flow frequencies are common at these locations. During the test period, lowest monthly FH score at remaining stations ranged from 0.81 to 0.84, which indicate that continuous hydropower operations are taking place during the dry season. The information regarding the low flows is helpful for many processes in the riverine ecosystem functioning. If the low flow gets altered to extremely low levels, ecological communities can get damaged.

6.5 Persistently Higher (PH), Persistently Lower (PL) and Persistently Very Low (PVL) Flows

There is a significant change in the FH scores of PH from the reference period to the test period, and the score changed from 0.82 (very small) to 0.47 (moderate). It shows that in the low flow season, high flow frequencies (> 75% per cent flow) are increased due to hydroelectric activity. This can lead to waterlogging problems. FH scores of PH at NSP and Vijayawada station altered largely as 0.30 and 0.31 respectively. De Sugur, Agraharam, and Yadgir have alterations in moderate condition with FH scores of 0.59, 0.54 and 0.59 respectively. This explains that continuous high flows are occurring in low flow seasons. It changes the river hydrological system affecting the aquatic lives that were adapted to a particular season. Mean of persistently lower (PL) indicators of five stations has altered from very small (FH=0.83) to small (FH=0.66). For Yadgir, the FH score for PL decreased by 33.33% of FH from the reference impact period and altered to moderate condition. For remaining stations, the score ranged from 0.63 to 0.76. This type of flows is very important in maintaining water quality and dissolved oxygen in a river. The overall PL analyses show that the river water quality in the entire basin deteriorated affecting not only the environment but also the human beings who are dependent on the river. For all stations, FH scores for PVL (<10% percentile flows) altered very slightly which ranged from 0.94 to 0.99 in the test period. These type of flows can be more helpful at extremely low flow condition to many organisms by maintaining minimum oxygen levels at the highly stressful condition.

6.6 Seasonality Flow Shift (SFS)

Seasonal Flow Shift analyses show that moderate alteration was observed at Yadgir with a FH score of 0.47; large alterations at De Sugur and Agraharam with scores of 0.40 and 0.36 respectively are seen from Table 6.1. Very large alterations were observed at NSP and Vijayawada stations with FH scores of 0.07 and 0.1 respectively.

The monthly average flow and seasonality flow shift for the reference period and test period are presented in Fig 6.1 (a, b, c, d, e). It is observed from the figures that the MAF during the reference period is higher than the corresponding MAF during the test period. This shows that the monthly streamflow has decreased during the period June to December and has increased from January to May. The month when the MAF is maximum is ranked as 1 followed by other months in the decreasing order of MAF. The month with lowest MAF is ranked 12. These are shown for both reference and test periods. It is seen from the figures that for the stations at De Sugur, Agraharam, NSP and Vijayawada, the maximum MAF for both reference and test periods occurs in the month of August, while for the station Yadgir, the maximum MAF for reference period occurs in the month of August while for the test period, the maximum MAF occurs in the month of September. The Fig. 6.1 (a, b, c, d, e) show the ranks of MAF for both the reference period and the test period for the five stations. The rankings are not changed for De Sugur for the months of June to December and March, and for the remaining months, the ranks are interchanged. For the station at Yadgir, the ranks are not changed for the months of July, October and December but the ranks of all the remaining months are altered. In the case of Agraharam, ranking of high flow season have changed except for the month of August. In the low flow season of March to May, no changes in the ranking was observed but increased MAF value, whereas months of January and February interchange their ranks. The MAF at

NSP and Vijayawada have similar rankings, except for the month of December. Severe alterations were observed in the month of June, which became the second driest month in the test period, whereas in the reference period it ranked sixth. Rankings in December, January, and May were shifted by one month while February and March shifted by three months.

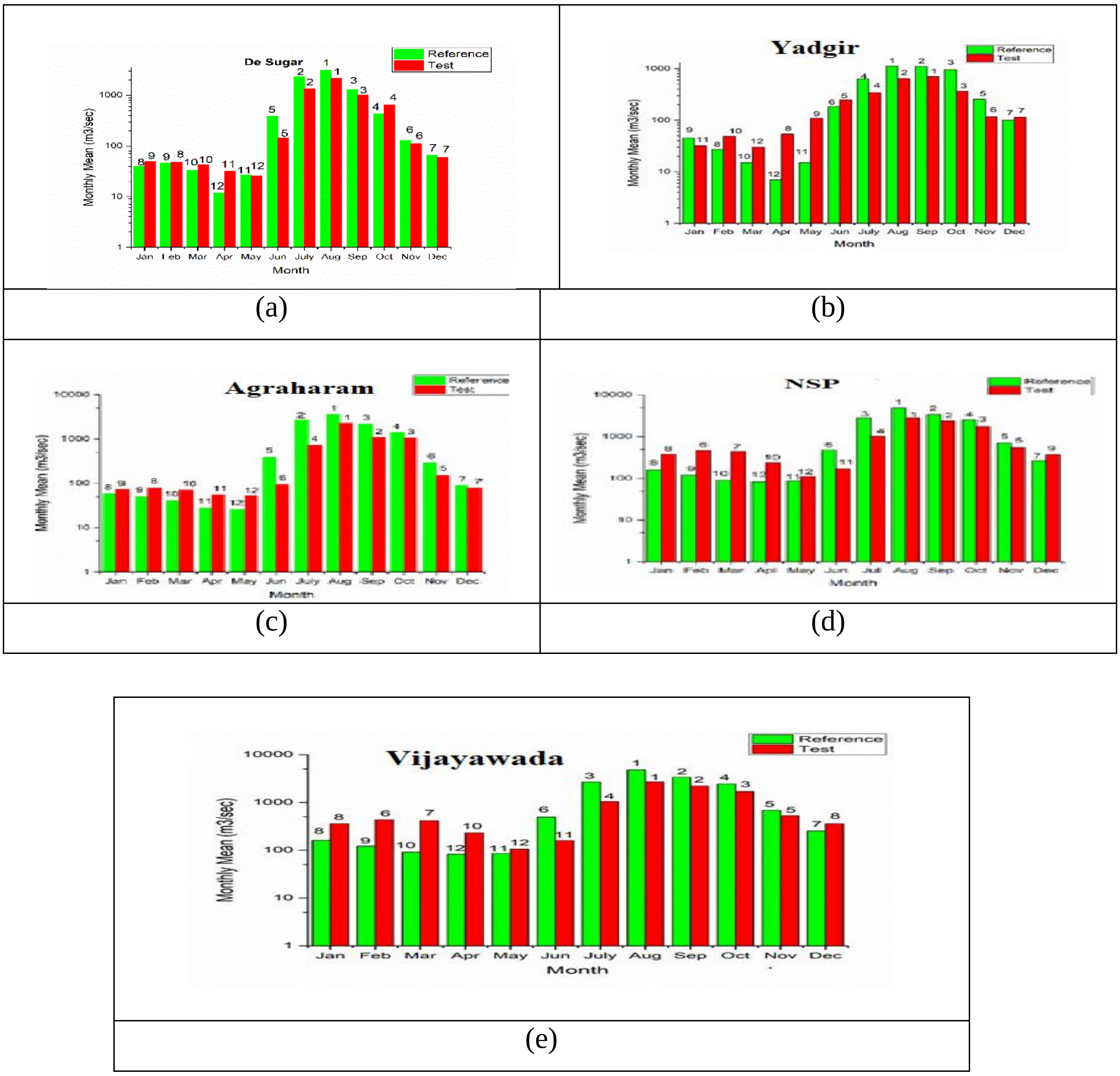


Fig.6.1 Monthly hydrograph with ranks for reference and test period for (a) De Sugur (b) Yadgir (c) Agraharam (d) NSP and (e) Vijayawada

6.7 Flood Flow Interval (FFI)

The natural hydrologic regime of most rivers is characterised by regular floods, which can strongly influence the distribution and abundance of aquatic organisms. Floods can provide opportunities for fish and other organisms to move from rivers to flood plains to access additional habitats. It is seen from the present study that the overall FFI mean score of 5 dams decreased by 26% of FH value, which indicates a reduction in fish and other organisms.

For each hydrological station, the overall FH score was determined by calculating the average of 9 hydrological indicators. The results show that the hydrological regime was least affected in the middle reach, moderately affected in Bhima and lower Krishna basins. FH increases with increase in the distance from the dam. The overall average FH score of reference and test impact period is 0.84 and 0.59 respectively. This indicates that even in the reference period, flow regimes do not attain the complete FH score due to the changes in the flow regimes. This study recommends to restore the natural flow regime characteristics in order to meet future water demands, both instream flow requirements and water development should be considered simultaneously.

6.8 Release of Minimum Flow

FH methodology is used to calculate EFR based on FH scores of 9 indicators. FH computes maximum EFR by keeping each indicator score as a '1' in the reference period. But recommending this EF values cannot work out due to the huge quantity of water required. The results indicate that at each station, FH score of '1' is obtained for all nine indicators for De Sugur, Yadgir, Agraharam, NSP, and Vijayawada when the flows are 86.88%, 81.03%, 93.57%, 88.5% and 87.6% of MAF. So, keeping in view the domestic demands, agricultural needs and industrial necessities, 30 % and 40 % of MAF are recommended which can maintain river in moderate and good conditions respectively, based on Tennant's method. The two recommendation assumed moderate risk and low risk to the environment. The low-risk regime achieved FH scores of 0.74, 0.73, 0.74, 0.74 and 0.73 with required 40% of MAF of each station as shown in the Table 6.2. The Table 6.2 also shows the moderate risk regime achieved through FH scores of 0.62, 0.61, 0.63, 0.62 and 0.60 and required 30% of MAF of each station. The scores are achieved in the reference period for average flow rates of 314 m^3/s, 18.4 m^3/s, 337 m^3/s, 530 m^3/s and 365 m^3/s at De Sugur, Yadgir, Agraharam, NSP, and Vijayawada stations respectively (Table 6.3). The scores achieved in the reference period with average flow rates of 236 m^3/s, 13.8 m^3/s, 253 m^3/s, 397 m^3/s and 365 m^3/s for De Sugur, Yadgir, Agraharam, NSP, and Vijayawada stations respectively (Table 6.3). FH scores of each indicator and corresponding mean monthly environmental flow requirements for the two options are also given in Table 6.2 and Table 6.3. FH scores for all indicators show small alteration condition for low risk regime option, whereas for moderate risk option representing all indicators, the scores are below large alteration condition. So, for this study low risk regime option is opted for environmental flow requirements for the Krishna River. In addition, a Flood Flow (FF) should be released once in 4 years during one of the high flow months. FF values range from 2,381 m^3/s to 36.8 m^3/s at Agraharam and Yadgir station respectively as shown in Table 6.4.

Table 6.2 Flow health score and corresponding Mean Annual Flow (MAF)

Indicator/ Dam	De Sugur		Agraharam		Yadgir		NSP		Vijayawada		Mean	
	30 % MAF	40 % MAF	30 % MAF	40 % MAF	30 % MAF	40 % MAF	30 % MAF	40 % MAF	30 % MAF	40 % MAF	30 % MAF	40 % MAF
HF	0.36	0.47	0.31	0.44	0.31	0.47	0.38	0.48	0.29	0.4	0.33	0.45
HM	0.34	0.44	0.32	0.41	0.33	0.45	0.36	0.46	0.28	0.4	0.32	0.43
LF	0.31	0.51	0.33	0.51	0.38	0.51	0.31	0.58	0.22	0.51	0.31	0.52
LM	0.36	0.68	0.36	0.66	0.41	0.67	0.34	0.64	0.35	0.76	0.36	0.68
PH	1	1	1	1	1	1	1	1	1	1	1	1
PL	0.28	0.56	0.25	0.57	0.31	0.61	0.23	0.54	0.26	0.55	0.26	0.56
PVL	1	1	1	1	1	1	1	1	1	1	1	1
SFS	1	1	1	1	1	1	1	1	1	1	1	1
FFI	1	1	1	1	1	1	1	1	1	1	1	1
FH Score	**0.62**	**0.74**	**0.61**	**0.73**	**0.63**	**0.74**	**0.62**	**0.74**	**0.6**	**0.73**	**0.62**	**0.73**

Table 6.3 Estimated monthly EFR at five stations to be released from the five dams to maintain a river environment in moderate (30% MAR) and fair condition (40% MAF) (m^3/s)

Months	Narayanapur		PD Jurala		Ujjani		Srisailam		Nagarjuna Sagar	
	30 % MAF	40 % MAF	30 % MAF	40 % MAF	30 % MAF	40 % MAF	30 % MAF	40 % MAF	30 % MAF	40 % MAF
January	16	22	17	22	14	19	48	64	46	61
February	12	16	15	19	8	11	35	47	31	42
March	5	7	12	16	4	6	25	34	21	31
April	2	3	8	11	2	2	25	33	20	28
May	11	15	7.92	10	4	6	25	33.5	20	29
June	137	182	107	143	57	76	148	197	142	187
July	770	1031	760	1011	179	238	856	1145	824	1009
August	901	1213	996	1333	353	471	1511	2014	1484	1989
September	502	669	594	792	330	440	1063	1412	1012	1406
October	361	482	414	552	289	385	750	1003	738	987
November	84	113	79.6	106	83	111	215	287	206	264
December	23	31	23.8	31	31	424	76	101	54	84
Average Flow	236	314	253	337	113	151	397	530	384	509

Table 6.4 Flood Flow (FF) to be released once in 4 years during one of the high flow months (m^3/s)

Dam	Narayanapur	PD Jurala	Ujjani	Srisailam	Nagarjuna Sagar
Flood Flow	741	2381	537	1930	1724

6.9 Nine Indicator Scores Achieved by DRM and GEFC Method.

DRM and GEFC methods are validated with the FH methodology. The monthly EFR values obtained by DRM and GEFC methods at five stations are replaced by the values obtained using the FH method. The FH score of the nine ecological indicators are determined for the EFR corresponding to FH method in DRM and GEFC. From the Table 6.5, it is observed that the scores of the nine indicators calculated with the EFR of DRM method are very close to the FH scores and the alteration range given by the two methods is almost the same, with very small alteration range. But score values calculated with the GEFC are in the moderate range when compared to the FH score values. One of the reasons is that the estimated EFR through GEFC in high flow season is very low. Total FH score of DRM method for all stations range from 0.60 (De Sugur) to 0.63 (Yadgir) and the total FH score of GEFC method for all dams range between 0.48 (De Sugur) and 0.50 (Yadgir).

Table 6.5 Comparing the score of nine indicators with the calculated EFR of three methods

Indicator Station	**De Sugur**			**Agraharam**			**Yadgir**			**NSP**			**Vijayawada**			**Mean**		
	FH	**DRM**	**GEFC**	**FH**	**DRM**	**GEFC**	**FH**	**DRM**	**GEFC**	**FH**	**DRM**	**GEFC**	**FH**	**DRM**	**GEFC**	**FH**	**DRM**	**GEFC**
HF	0.47	0.41	0.37	0.44	0.4	0.33	0.47	0.46	0.34	0.48	0.45	0.41	0.4	0.43	0.38	0.45	0.43	0.36
HM	0.44	0.41	0.36	0.41	0.39	0.41	0.45	0.44	0.35	0.46	0.44	0.37	0.4	0.41	0.35	0.43	0.41	0.36
LF	0.51	0.42	0.33	0.51	0.47	0.33	0.51	0.49	0.42	0.58	0.54	0.34	0.51	0.52	0.31	0.52	0.48	0.34
LM	0.68	0.81	0.41	0.66	0.84	0.36	0.67	0.91	0.46	0.64	0.82	0.38	0.76	0.79	0.35	0.68	0.83	0.39
PH	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
PL	0.56	0.55	0.31	0.57	0.52	0.31	0.61	0.59	0.36	0.54	0.52	0.32	0.55	0.51	0.31	0.56	0.53	0.32
PVL	1	0.81	0.61	1	0.84	0.63	1	0.86	0.62	1	0.81	0.61	1	0.79	0.60	1	0.82	0.61
SFS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
FFI	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0
FH score	**0.74**	**0.60**	**0.48**	**0.73**	**0.60**	**0.48**	**0.74**	**0.63**	**0.50**	**0.74**	**0.62**	**0.49**	**0.73**	**0.60**	**0.47**	**0.73**	**0.61**	**0.48**
Alteration condition	**S**	**S**	**M**	**S**	**S**	**M**	**S**	**S**	**M**	**S**	**S**	**M**	**S**	**S**	**M**	**S**	**S**	**M**

S= Small; M= Medium

6.10 Summary and Conclusion

In this study, a comprehensive approach for environmental flow analysis for the downstream of the five dams under FH methods is presented. The FH approach combinedly gives the hydrological alteration and environmental flow requirements values. The following conclusions can be drawn from the FH analysis.

- The mean FH score ranges from 0.85 to 0.86 in reference impact period and from 0.54 to 0.62 in the test period.
- The seasonal analyses demonstrated that improper operation of the dams leads to the high seasonal flow shifting.
- EFRs are estimated by opting two recommendations (Low-risk and Moderate risk to environment) based on Tennant's recommendations.
- The low-risk regime achieved FH scores of 0.74, 0.73, 0.74, 0.74 and 0.73 with required 40% of MAF for each dam.
- The moderate risk regime achieved FH scores of 0.62, 0.61, 0.63, 0.62 and 0.60 and required 30% of MAF for each dam.
- DRM and GEFC methods are validated with the FH methodology.
- It is observed that the nine indicators scores calculated with the EFR of DRM method are very close to the FH score.

CHAPTER 7

HYDRAULIC AND HABITAT ANALYSIS

7.1 General

In the present chapter, hydraulic analysis was carried out to determine the acceptable flow regime for the aquatic species in the study area. HEC-RAS model was used for the analysis. The goal of hydraulic model is to determine the maximum and minimum water depths and velocity limits for the EFR flow conditions which are already calculated. This is done because suitable velocity and depth of the flow in the stream provides the condition for maximising the food production area below the water surface for aquatic life. So, the rate at which the hydraulic parameters change with the discharge is quite important. The full range of calculated monthly EFR values of three methods are used in determining the physical characteristics of the Krishna River using the relationships of the hydraulic analysis. This analysis is done for each of the five dams from the upstream side to downstream side. The results of the HEC-RAS modelling agree with the observed data in the field as described in the Section 3.7. HEC-RAS outputs are obtainable in both, tabular and graphical form. In graphical form, HEC-RAS output can be seen as general profiles, rating curves, water surface profiles, and X-Y-Z perspective plots. HEC-RAS results are presented in this Chapter in tabular form. The calculated hydraulic parameters values are used to create instream habitation model. Hydraulic model values are used in habitation analysis.

In the river environment, "instream habitat" depends on the depth, speed, and surface area of the water. Fishes can survive within the river with good instream conditions (depth and velocity of flow) than the poor quality of an instream habitat structure. So, in this study, an attempt is made to explain the rate at which the calculated EFR are providing the minimum and maximum water depth and velocity in the Krishna River using the results of the hydraulic analysis. In the absence of detailed information about all the various species and communities in a river ecosystem, fishes are taken as key indicator species. The species of fishes found in Krishna River includes Catfish, Carps, Anguilla, Notopterus, Silonia, Mystus, and Seenghala. Information concerning physical habitat requirements of fish present in the river was collected from Fisheries Department Survey Report (2019). Habitat Suitability Curves (HSC) were developed as shown in the Fig. 7.1 and Fig. 7.2 to estimate the habitation in the river. It is seen from the HSC that water depth above 0.4m and velocities in the range of 0.4m/s to 0.8 m/s are suitable for fish habitation. In the habitat modelling process, water depth and velocity values are integrated with the HSC for fishes to get the available habitations as a function of an EFR. The main reason to introduce HSC is that the hydraulic parameters change with the changes of EFR values, which can cause change in the quality and quantity of habitats available in the river. The general principle behind the habitat modelling within HSC is based on the assumption that aquatic species will respond to changes in the hydraulic environment. Finally, Habitat Suitability Index (HSI) is calculated as a function of discharge and fishes habitat suitability using HSC.

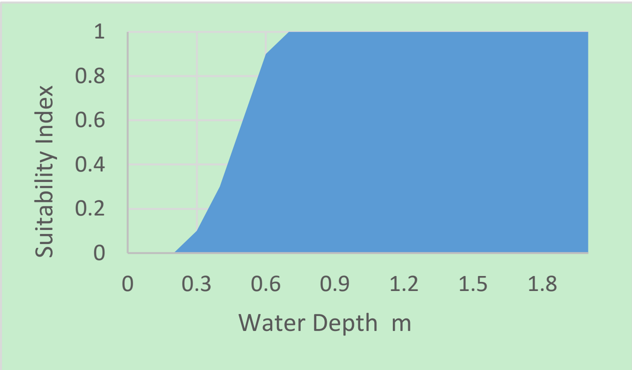


Fig.7.1 Water Depth Habitat Suitability Curve

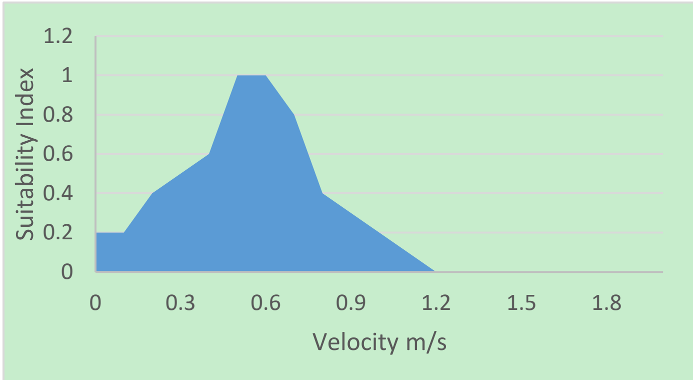


Fig.7.2 Flow Velocity Habitat Suitability Curve

7.2 Hydraulic Analysis

The hydraulic analysis is carried out for the cross section under the downstream of each dam with the calculated EFR flow values by each of the three methods. The water surface profile runs for the three methods at different points under the downstream of the five dams and the results of the hydraulic analysis are explained in this section. Reach-averaged hydraulic parameters with each method for each dam were computed and summarised in Table 7.1, Table 7.2 and Table 7.3.The results show that the water levels increase with increasing flow rate. At some points, the hydraulic results had decreased values because of the existence of levees to protect agricultural area in the floodplain of Krishna River.

7.2.1 DRM hydraulic analysis

Table 7.1 shows that the results of the hydraulic analysis of DRM method using HEC-RAS model. It is seen from the table that the velocity ranged from 0.12 m/s to 1.05 m/s under Narayanapur dam, 0.12 m/s to 1.06 m/s under Ujjani dam, 0.10 m/s to 0.64 m/s under PD Jurala dam, 0.19 m/s to 0.96 m/s under Srisailam dam, and 0.33 m/s to 1.08 m/s under Nagarjuna

Sagar. The velocity has a high variability between cross sections. At the same time, water depth ranged from 0.23 m to 2.88 m under Narayanapur dam, 0.26 m to 1.98 m under Ujjani dam, 0.26 m to 2.84 m under PD Jurala dam, 0.43 m to 3.08 m under Srisailam dam, and 0.45 m to 3.16 m under Nagarjuna Sagar. According to DRM results, the velocity ranged from 0.10 m/s to 1.08 m/s and water depth ranged from 0.23 m to 3.16 m throughout the basin,.

Table 7.1 Average hydraulic parameters calculated with the help of the EFR by the DRM method

Downstream of the dam	Parameter	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Narayanapur	Depth (m)	0.43	0.43	0.38	0.23	0.28	0.93	2.12	2.88	2.12	1.43	0.91	0.53
	Velocity (m/s)	0.20	0.22	0.18	0.12	0.16	0.46	0.84	1.05	0.84	0.74	0.43	0.31
Ujjani	Depth (m)	0.54	0.39	0.31	0.26	0.29	0.62	1.34	1.98	1.64	1.91	1.07	0.68
	Velocity (m/s)	0.20	0.16	0.14	0.12	0.12	0.26	0.66	1.06	0.81	0.85	0.45	0.35
PD Jurala	Depth (m)	0.48	0.43	0.36	0.33	0.26	0.66	2.04	2.84	2.36	2.33	0.86	0.58
	Velocity (m/s)	0.23	0.20	0.18	0.13	0.10	0.31	0.48	0.64	0.57	0.56	0.34	0.26
Srisailam	Depth (m)	0.68	0.63	0.53	0.48	0.43	0.73	1.53	3.08	2.57	2.61	1.26	0.83
	Velocity (m/s)	0.28	0.26	0.23	0.22	0.19	0.34	0.67	0.96	0.78	0.82	0.49	0.43
Nagarjuna Sagar	Depth (m)	0.71	0.60	0.55	0.51	0.45	0.74	1.61	3.16	2.62	2.64	1.30	0.86
	Velocity (m/s)	0.38	0.36	0.35	0.34	0.33	0.46	0.84	1.08	0.90	0.91	0.61	0.55

7.2.2 GEFC hydraulic analysis

Table 7.2 shows the results of the hydraulic analysis by GEFC method. The results of the GEFC using HEC-RAS modelling show that the velocity through the system ranged from 0.09 m/s to 0.91 m/s under Narayanapur dam, 0.12 m/s to 0.83 m/s under Ujjani dam, 0.1 m/s to 0.6 m/s under PD Jurala dam, 0.17 m/s to 0.86 m/s under Srisailam dam, and 0.33 m/s to 1.01 m/s under Nagarjuna Sagar. The velocity has a high variability between cross sections. Water depth ranged from 0.19 m to 2.31 m under Narayanapur dam, 0.29 m to 1.84 m under Ujjani dam, 0.25 m to 2.66 m under PD Jurala dam, 0.4 m to 2.74 m under Srisailam dam, and 0.42 m to 2.71 m under Nagarjuna Sagar. According to the GEFC method, velocity and water depth ranged from 0.09 m/s to 1.01 m/s and from 0.19 m to 2.74 m, respectively.

Table 7.2 Average hydraulic parameters calculated using the EFR of the GEFC method

Downstream of the dam	Parameters	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Narayanapur	Depth (m)	0.38	0.38	0.31	0.28	0.19	0.49	1.46	2.31	2.24	0.99	0.48	0.44
	Velocity (m/s)	0.18	0.19	0.12	0.16	0.10	0.32	0.75	0.91	0.86	0.45	0.34	0.23
Ujjani	Depth (m)	0.34	0.31	0.29	0.31	0.31	0.53	0.91	1.84	1.37	1.48	0.91	0.68
	Velocity (m/s)	0.17	0.15	0.12	0.14	0.14	0.19	0.41	0.83	0.69	0.71	0.41	0.35
PD Jurala	Depth (m)	0.36	0.34	0.33	0.25	0.26	0.51	1.98	2.66	1.72	1.88	0.66	0.47
	Velocity (m/s)	0.23	0.09	0.13	0.10	0.10	0.31	0.44	0.60	0.48	0.51	0.31	0.23
Srisailam	Depth (m)	0.64	0.53	0.43	0.40	0.43	0.73	1.34	2.74	1.76	1.69	1.29	0.9
	Velocity (m/s)	0.27	0.25	0.19	0.17	0.19	0.34	0.62	0.86	0.75	0.71	0.46	0.4
Nagarjuna Sagar	Depth (m)	0.63	0.53	0.44	0.42	0.44	0.74	2.42	2.71	1.76	1.71	1.34	0.9
	Velocity (m/s)	0.36	0.35	0.34	0.33	0.33	0.46	0.72	1.01	0.83	0.78	0.57	0.38

7.2.3 Flow health hydraulic analysis

The results of the flow health and HEC-RAS modelling show that the velocity through the system ranged from 0.12 m/s to 1.10 m/s under Narayanapur dam, 0.12 m/s to 1.06 m/s under Ujjani dam, 0.13 m/s to 0.64 m/s under PD Jurala dam, 0.22 m/s to 1.09 m/s under Srisailam dam, and 0.34 m/s to 1.09 m/s under Nagarjuna Sagar (Table 7.3). The velocity has a high variability between cross sections. The water depths ranged from 0.23 m to 2.76 m under Narayanapur dam, 0.29 m to 2.21 m under Ujjani dam, 0.33 m to 2.84 m under PD Jurala dam, 0.53 m to 3.1 m under Srisailam dam, and 0.52 m to 3.04 m under Nagarjuna Sagar. The velocity and water depth distribution ranged from 0.12 m/s to 1.09 m/s and from 0.23 m to 3.1 m, throughout the basin.

The average probable extent of low depth was determined by GEFC, and the high depth was observed for the FH method. The velocity of the water in the low flow season is very low for three methods. But the larger water spread area will provide more space for habitation.

The depths of the flow observed in the low flow season for the months March, April and May under Narayanapur, Ujjani and PD Jurala are not satisfactory and inadequate for habitation. From this, it can be concluded that the flow values suggested by three methods are not supporting the suitable habitat for species in these months. The discharges of 14 m^3/s, 10m^3/s, 15 m^3/s, were estimated as the point of inflection of the suitable habitats under the three dams respectively. The reduction of discharge below this inflection point is considered as harmful to these species, as the availability of suitable habitats is greatly reduced. Furthermore, the increase in discharge above these values has benefit for many of these species. Hence, the minimum flow requirement of the selected fish species was estimated as 15 m^3/s, during the dry season (i.e. March, April and May) of the Krishna River.

Table 7.3 Average hydraulic parameters calculated using EFR by the Flow Health method

Downstream of the dam	Parameters	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Narayanapur	Depth (m)	0.43	0.38	0.28	0.23	0.38	1.18	2.56	2.76	2.24	1.51	1.09	0.52
	Velocity (m/s)	0.22	0.19	0.16	0.12	0.18	0.53	0.97	1.10	0.86	0.81	0.49	0.32
Ujjani	Depth (m)	0.53	0.39	0.31	0.29	0.32	0.72	1.50	2.21	2.06	1.99	1.01	0.66
	Velocity (m/s)	0.19	0.16	0.14	0.12	0.14	0.38	0.72	1.06	1.01	0.87	0.44	0.34
PD Jurala	Depth (m)	0.44	0.43	0.36	0.34	0.33	0.87	2.67	2.84	2.41	2.04	0.82	0.56
	Velocity (m/s)	0.23	0.20	0.18	0.13	0.13	0.34	0.61	0.64	0.59	0.56	0.31	0.25
Srisailam	Depth (m)	0.68	0.63	0.53	0.53	0.53	1.11	2.60	3.10	2.85	2.57	1.21	0.81
	Velocity (m/s)	0.28	0.26	0.23	0.22	0.23	0.45	0.79	1.09	0.85	0.81	0.47	0.34
Nagarjuna Sagar	Depth (m)	0.68	0.64	0.54	0.52	0.53	1.12	2.54	3.04	2.86	2.56	1.20	0.79
	Velocity (m/s)	0.38	0.36	0.35	0.34	0.35	0.56	0.90	1.09	1.01	0.86	0.58	0.46

7.3 Habitation Modelling

In the present study, habitat modelling approach was assumed to simulate and assess the ecological effects of physical aquatic habitat changes due to the regulated flow, and to assist in making decisions on acceptable flow regime necessary for aquatic species. Habitat model was used to define the habitation of the river in terms of velocity and depth. The depth and velocity attributes vary with the simulated changes in discharge, causing changes in the amount and quality of the available habitat. In the modelling process, hydraulic of the river integrated with the habitat suitability criteria for selected fishes to obtain the available physical habitat as a function of a discharge. The general principle behind the habitat modelling programs is based on the assumption that aquatic species will respond to changes in the hydraulic environment.

These changes are simulated for each section in a defined reach of the river. The reach simulation takes the form of a multidimensional matrix of the calculated surface area of a stream having different combinations of hydraulic parameters such as depth and velocity. Finally, HSI of the fishes was calculated as a function of discharge and species habitat suitability using HSC.

The HSI was calculated based on the values of water depth and flow velocity under each dam for each of the methods. The calculated HSI values are classified into five categories, as poor (0.0-0.2), moderate (0.3−0.4), fair (0.5−0.6), good (0.7−0.8) and excellent (0.9−1.0), according to the USFWS (1981) habitat report. Table 7.4 shows that three approaches are providing excellent habitats under the downstream of Srisailam and Nagarjuna Sagar dams. Good habitat condition is seen under Narayanapur and Ujjani dams. PD Jurala falls in fair condition under GEFC method. Interestingly DRM method giving higher habitation compared to the FH and GEFC method. This is because the FH method results in higher velocity values which cause a decrease in the habitation, but this type of velocity is good in transporting sedimentation and wastage influences. GEFC is giving low water depth and low water velocity values.

Table 7.4 Habitat Suitability Index

Methods	Dams				
	Narayanapur	Ujjani	PD Jurala	Srisailam	Nagarjuna Sagar
DRM	0.73 (G)*	0.67 (G)	0.63 (G)	0.88 (EX)*	0.90 (EX)
GEFC	0.68 (G)	0.60 (G)	0.59 (F)*	0.81 (EX)	0.82 (EX)
FH	0.69 (G)	0.63 (G)	0.61 (G)	0.85 (EX)	0.80(EX)
*F = Fair G = Good EX = Excellent					

7.4 Summary and Conclusions

In this study, a comprehensive approach for habitation suitability index analysis for the downstream of the five dams using three methods is presented. The approach combines the hydraulic and habitation model for calculating the HSI in a spatial context. Hydraulic analysis has an important role in accurately assessing the habitation. Two hydraulic variables (i.e. depth, velocity) are estimated by using HEC-RAS modelling. For this higher resolution DEM with fully 1D hydrodynamic model is used to provide more detailed hydraulic analysis for this study. Hydraulic analysis is quantified by using calculated EFR. Spatial variability of hydraulic analysis is also carried out. This study provides significant potential for better hydraulic analysis in the future at river basin scale.

In terms of providing habitation, the DRM is giving better results than the GEFC and FH method. More importantly, the results from the hydraulic analysis provide more useful information to choose the better EFR in the months of March, April, and May. The observation from the study is that the river needs a minimum discharge of 15 m^3/s for minimum habitation regardless of the season. The results of this study will help the policy makers and stakeholders to estimate the EFR in this river basin based on hydraulic and habitation context. In addition, it also provides significant information about the habitation situation in the basin for making preparedness plan, including aid and relief operations for habitation loss areas.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1 Summary

Rapid growth in human population has led to the depletion of global natural fresh water resources to meet various human needs. These hydrological changes caused huge damage to ecosystem including loss of various species. The damage and loss of life caused by flow changes could be higher in the future due to increasing human water demand owing to climate change. Assessment of the change of flow characteristics under the context of anthropogenic activities plays a significant role in managing the water resources. Quantifying the environmental flow requirements associated with the changes of flows allows local dam authorities to plan the management of water resources without damaging our ecosystem. This study focusses on the impact of the dams operation on hydrological alterations and the existing flow condition within the basin to quantify the freshwater needed to improve the basin health.

To investigate the hydrological alteration, IHA and FH tools are used to extract the affected flow events. IHA calculates 33 hydrological flow parameters by comparing pre and post dam data. However, IHA cannot be used in the case of assessment of environmental flow requirements, because it does not provide ecologically acceptable flow information. Unlike the IHA, which uses a large number of parameters, FH focussed on main ecological indicators and provides more information about on EFR.

Environmental flows are assessed using three methods viz. (i) Desktop Reserve Model (DRM), (ii) Global Environmental Flow Calculator (GEFC) based on flow duration curve approach and (iii) Flow Health (FH). Among three methods, GEFC calculates EF values based on flow duration curve which involved statistical approach, and recommended EFR values are less while comparing with other two methods. When the GEFC recommended EFR values are integrated with hydraulic analysis, the results are not supporting the minimum habitation requirements in a river during the low flow season. DRM and FH methods suggest approximately the same EF values and also support the habitations in the river. The hydraulic analyses revealed that recommended EF values with the three methods for the months of March, April and May did not provide good habitat in the river. So, by using hydraulic habitat analysis, new EFR values are recommended for the months of March, April and May. Non-attainment analysis explained how calculated EFR values are not maintained in the basin in post period.

The research reported in this thesis contributes towards assessing the hydrological alteration under anthropogenic activities and environmental flow requirements at the river basin scale. Initially, the potential impact of anthropogenic activities on hydrological alteration is evaluated for the Krishna River basin, by removing climatic effects. Finally, the last part of this thesis contributes towards developing EFR obtained using hydrological models and hydraulic model with different tools.

8.2 Conclusions

The hydrologic analysis indicated that changes had occurred in the hydrology of the Krishna River from the pre-period to the post-impact period. The following conclusions can be drawn from the hydrologic analysis:

- Construction and operation of the reservoirs, with the aim to reduce flood disaster and water storage, caused significant hydrologic alterations along the Krishna River.
- The peak flows in August through October observed in the post-period have decreased in magnitude from the pre-period at all the gauging station.
- Among all the parameters of the Indicators of Hydrologic Alteration, February, March, April, August, September, 90-day minimum, 90-day maximum, 30-day minimum, Base flow index, June and July represent the most important alterations caused by the dams.
- The seasonal analyses demonstrated that improper operation of the dams lead to the high seasonal flow shifting.
- The spatial-temporal hydrologic alterations are different among the five stations taken up for the study. It is implied that the overall degree of hydrologic alteration change at Yadgir station and PD Jurala was moderate and De Sugar it is high. More ecological treatments should be made in the upper middle and lower Krishna River.
- The ongoing and proposed construction of multiple dams in the Krishna River will cause cumulative hydrological alteration. So, ongoing projects should introduce innovative designs that minimises adverse ecological impact
- The results obtained by the approach presented in the study shows option for reducing the overall cumulative impacts on the downstream of the dams.
- To maintain the river in Class (B) and Class (C) of DRM method and GEFC method, 36.12 % and 25.87 % of MAF will be required.

- The results indicated that the EFR proposed using DRM and FH show almost the same alteration condition. GEFC shows large deviation.
- The minimum flow requirement of the selected fish species found in the river was estimated to be 15 m^3/s, during the dry season (i.e. March, April and May) of the Krishna River.
- Results from the HEC-RAS model were used to investigate the relationships between the hydraulic flow characteristics and the natural environmental flows. Flow need to be varied in different months of the year to preserve the riverine ecosystems and maintain their services.
- The results of this study will be very helpful for the future management of water resources and will be significant for further understanding of the human impacts (e.g., multipurpose dam projects) on hydrological regimes in the river.
- The study is expected to help take management decisions for efficient water resource allocation, enhancing IWRM, and maximising ecological benefits in the river. Moreover, it will provide hydrologic and hydraulic information for cross-border collaboration for integrated management of Shared Transboundary Ecosystems (STEs) in the basin. However, environmental flow assessment is a continuous process which needs to be updated and improved by using higher resolution data and incorporating future data monitoring plans.

8.3 Research Contribution

- The Environmental flow assessment (EFA) practice in India is of recent origin. This study contribution to the limited literature on EFA in India and particularly to the south India region where in a large number of hydropower projects are being implemented.
- Flow requirements downstream of river in India are prescribed in terms of certain minimum flow or in terms of hydrological indices. This study is important as it attempts to incorporate hydrologic, hydraulic and ecological aspects in EFA and provides scientific basis for prescription of EF.
- Flow related impacts of anthropogenic activities are spread over a river reach and associated tributary catchments. The present study considers environmental flow requirements of the tributary catchments also as these are distinct from environmental flow requirement in a river reach.

- As an improvement over the previous hydrological studies of Krishna River basin, the methodology proposed in this study is based on three models.
- Hydrologists have used IHA analysis to evaluate the potential hydrological alteration in rivers. This information can provide valuable knowledge for designing infrastructure, reservoir system operational plans, and environmental assessment in Krishna River. Furthermore, Flow Health approach is better suited for environmental flow analysis and to arrive at better and reliable accurate estimates of environmental flow than corresponding Desktop Reserve Model (DRM) and Global Environmental Flow Calculator (GEFC). However, in India many studies used GEFC to assess the EFR at global as well as regional scale while there were no studies which used Flow Health approach. Even the studies carried out using GEFC approach mostly considered only a single dam.
- Indicator of hydrological alteration (IHA) is widely used for multivariate analysis for estimating the characteristics of flow impacted by anthropogenic activities. IHA can give a comprehensive understanding in assessment of the hydrological alteration. This approach does not recommend or guide in estimation of EFR. Therefore, it is essential to study the hydrological alteration related with EFR. The main purpose of introducing FH method is to calculate EFR based on the nine most important ecological indicators. The advantage of FH methodology is that the method has the capability to estimate how much alteration can be reduced by considering the calculated EF values, while the other two methods, viz., DRM and GEFC are not able to describe about it.
- The surveyed cross-sections and high-resolution DEM along with water depth and velocity hydrograph are used as the input data for the HEC-RAS model to simulate the hydraulic analysis. Furthermore, the habitation modelling approach, is developed by integrating hydraulic analysis data in this study. The water depth and velocity obtained from the hydrodynamic model are used to calculate habitat suitability curve for the study area under the environmental flow context.

8.4 Recommendations

i. With the ongoing and proposed construction of multiple dams in the Krishna River, cumulative hydrological alteration is expected to take place. So, ongoing projects should introduce innovative designs that minimise adverse ecological impact.

ii. To ensure the provision of sustainable water flows in the river the following recommendations are made.
    a. Continuous collection of data on hydrology, hydraulics, and ecology.
    b. Development of a framework of joint management of this transboundary river and sharing of hydrological data between states.
    c. Consideration of environmental flows at the planning stage of future water resources development projects in the river.

iii. Depth and velocity of habitat suitability criteria have an enormous influence on EF assessment and so an extensive research plan may be useful in developing the criteria.

iv. Only a few species have been considered for this study. Steps may be made to consider other dependent species in future studies.

v. Flow data is an important aspect of this study. So, continuous data collection is needed for the post period too.

vi. The cross sections for this study have been assumed as unchanged, but they vary with flow. Accordingly, further research can be taken with varying cross sections with different flows conditions.

vii. A detail study can be carried out to specify the actual wetland connectivity flow requirement. It is essential to include all the wetlands dependent on Krishna River system for future studies.

8.5 Scope Future Research

As stated earlier, research on EFA in India is of recent origin. In the present study, several aspects of EFA as relevant to dams in Krishna River region have been dealt through case study of EF on the Krishna River. The EFA study needs to be carried out for other tributaries in Krishna River. These rivers are more influenced by anthropogenic activities and have great religious significance to vast population from all over the country. As is evident from coverage of various aspects, multidisciplinary study requiring expertise from various fields is needed for EFA. Field based studies of Indian rivers in the following areas are suggested for improving EFA methodology:

i. Hydraulic habitat requirements for remaining existing species (particularly aquatic life) in the Krishna River.

ii. Water quality assessment based on abundance of macroinvertebrates at different levels of pollution.

iii. Study and inventory of the biodiversity to increase the scientific understanding of the riverine ecosystems at species level.

iv. Economic valuation of the ecosystem services in the river.

v. Modelling the estuary to relate salinity with freshwater inflows, sediment distribution, and water quality.

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- **Uday Kumar, A** and Jayakumar, K. V. (2018). "Assessment of hydrological alteration and environmental flow requirements for Srisailam dam on Krishna River, India". *Water Policy*, 20 (6), pp 1176-1190. https://doi.org/10.2166/wp.2018.203**. (SCI).**
- **Uday Kumar, A** and Jayakumar, K. V. (2018). "Assessment of Environmental Flows using Hydrological Methods for Krishna River, India". Advances in Environmental Research, 7 (3), pp 161-175. https://doi.org/10.12989/aer.2018.7.3.161. (**ESCI**).
- **Uday Kumar, A** and Jayakumar, K. V. (2020). "Hydrological alterations due to anthropogenic activities in Krishna River Basin, India". *Ecological Indicators*, 108. https://doi.org/10.1016/j.ecolind.2019.105663. **(SCI, Scopus).**
- **Uday Kumar, A** and Jayakumar, K. V. (2020)."Modelling of Environmental Flow Requirements using Hydraulic and Habitation Models". Ecological Indicators https://doi.org/10.1016/j.ecolind.2020.107046. **(SCI, Scopus)**
- **Uday Kumar, A** and Jayakumar, K. V. Assessment of Flow Regime Alteration in the Krishna River Basin. (Minor Comments Submitted, ISH Journal of Hydraulic Engineering) (**Scopus**).

Conference Proceedings

- **Uday Kumar A** and K V Jayakumar (2016) "Hydrological Approach to Develop Environmental Flow Duration Curve" National Conference on Water Resources and Flood Management with Special Reference to Flood Modelling, HYDRO 2016, Indian Society for Hydraulics, Surat, 14-15 October.
- **Uday Kumar A** and K V Jayakumar (2017) "Assessment of Hydrological Alteration due to Human Intervention on River Flow Regimes" 22nd International Conference on Hydraulics, Water Resources and Coastal Engineering, HYDRO 2017, organised by the Indian Society of Hydraulics, Ahmedabad, 21-23 December.
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