

ENVIRONMENTAL FLOW ASSESSMENT USING HYDRODYNAMIC MODELLING

काशी हिन्दू
विश्वविद्यालय



BANARAS HINDU
UNIVERSITY

THESIS

SUBMITTED IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

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in

Agricultural Engineering

(Soil and water conservation engineering)

Submitted by

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Dear Sir,

We have great pleasure in forwarding the thesis entitled **“Environmental flow assessment using hydrodynamic modelling”** submitted by **Mr. Pavan Kumar Harode, I.D. No.: 17SWE08, Enrolment No.: 397637** in partial fulfillment of the requirements for the award of the degree of **Master of Technology in Agricultural Engineering (Soil and Water Conservation Engineering)**, Department of Farm Engineering, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi.

This is to certify that the work has been carried out solely by **Mr. Pavan Kumar Harode** under my supervision and guidance and his findings and data presented herein are genuine and original to the best of my knowledge and belief and no part of the work has been submitted for any other degree or distinction.

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By

PAVAN KUMAR HARODE

THESIS SUBMITTED IN THE PARTIAL FULFILMENT OF
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DEPARTMENT OF FARM ENGINEERING
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INTRODUCTION

1.1 Background

Water is very important for all living organism on the earth. Life is not possible without water. The highest water is found in the ocean, from the rain or the melting of the ice on the polar the rivers join the sea. During the 1960s, the developed nations primarily concentrated on the maximization of water management through flood protection, water supply and hydropower generation. As a result, there was huge modification made in the flow of the rivers due to the construction of impoundments such as dams and weirs, extraction of water for agriculture, irrigation and urban purposes, maintain the flow for navigation purposes, drainage water inflow, and flood management structures (Dyson *et al.*, 2003; Pastel and Richter, 2003). These interventions have caused significant alteration of flow regimes mainly by reducing the total flow and affecting the variability and seasonality of flows. It is estimated that more than 60% of the world's rivers are fragmented by hydrological alterations (Revenga *et al.*, 2000). Rivers are the main carriers of flora, fauna, minerals etc. If they are excessively blocked, it will result in degradation of their ecosystems. This has led to widespread degradation of aquatic ecosystems (Millennium Ecosystem Assessment, 2005).

This phenomenon has given rise to the concept of environmental flows. Environmental flows serve to represent water allocation for ecosystems. As ecosystems, in turn, provide services to people, providing for environmental flows is not exclusively a matter of sustaining ecosystems but also a matter of supporting livelihoods of village people who make direct use of river water for a variety of purposes including religious worship. Variability and seasonality of flows in tropical countries such as India are characterized by a high percentage of annual rainfall (70% to 85%) occurring in monsoon season (June/July to September/October). Tropical monsoon hydrology necessitates the development of storage and flow diversion schemes on rain-fed and peninsular river for multipurpose utilization of water particularly for hydropower generation and irrigation for which high demand exists throughout the year.

1.2 Environmental Flows

Brisbane Declaration (2007) defines E-Flows as the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems. Thames and King (1998) opined that the amount of water that is left in a river, or released into it from a reservoir, is called environmental flow. Environmental flow maintains valuable features of ecosystem of river. It refers to the sufficient water quantity considered for protection of structure and function of river ecosystem and its dependent species. It means sufficient water is remain in rivers, which is maintained downstream of river. Which gives environmental, social and economic benefits. Environmental flow assessments to maintain downstream river ecosystems, renewable natural resource production systems and associated living things of river. Environmental flow assessment is a deal between water resources development and maintenance of a river in ecologically acceptable condition.

1.3 Significance of Environmental Flows in Aquatic Ecosystem

An ecosystem is a natural unit consisting of all plants, animals, and micro-organisms (biotic factors) in an area functioning together with all of the non-living physical (abiotic) factors of the environment. A river reach may be considered as an aquatic ecosystem and its catchment as a terrestrial ecosystem. These two ecosystems support distinct ecologies. Globally, there is a growing recognition of the need for safeguarding ecosystems when managing waters to meet human demands (Dugan *et al.*, 2002; Instream Flow Council, 2002; Postel and Richter, 2003; Dyson *et al.*, 2003).

A goal of integrated water resources management is to ensure that the efficient use of water and related resources does not compromise the sustainability of vital ecosystems (GWP, 2000; GWP, 2003). This entails finding the balance between the short-term needs of social and economic development and the protection of the natural resource base for the longer term. An important challenge is, therefore, to balance water allocation between different users and uses (GWP, 2000). Ecosystems are the silent water users who have frequently been omitted from water allocation decision-making. Ecosystems, however, provide a wide range of valuable services to people (GWP, 2003; Millennium Ecosystem Assessment, 2005). In India, the livelihood of rural people to a large extent depends directly on the provision of ecosystem services. The marginalization of ecosystems in water resources management and the associated degradation or loss of ecosystem services have resulted in economic costs, in terms of declining profits, remedial measures, damage repairs and lost

opportunities. The highest costs, however, are typically borne by people depending directly on ecosystem services (Emerton and Bos, 2005; Millennium Ecosystem Assessment, 2005; Pearce *et al.*, 2006).

In several cases, maintaining ecosystems has proven to be a more cost-effective way of providing services than employing artificial technologies (Emerton and Bos, 2005). Thus, recognizing the full value of ecosystem services, and investing in them accordingly, can safeguard livelihoods and profits in the future, save considerable costs and help achieve sustainable development goals. Failing to do so may seriously jeopardize any such efforts (Russell *et al.*, 2001; Costanza, 2003; Dyson *et al.*, 2003; Emerton and Bos, 2005; Millennium Ecosystem Assessment, 2005; Pearce *et al.*, 2006). Many factors, such as water quality, sediments, food-supply and biotic interactions, are important determinants of riverine ecosystems. However, an overarching master variable is the river's flow regime (Poff *et al.*, 1997; Bunn and Arthington, 2002). This recognition of flow as a key driver of riverine ecosystems has led to the development of the environmental flows concept (Dyson *et al.*, 2003).

1.4 Objectives of the Study

The main objective of this research is to evaluate various approaches being used for estimation of environmental flow requirement of rivers and to formulate recommendations to apply a suitable approach for estimating the environmental flows of Godavari River. The study has been envisaged with the following objectives:

- a) To identify the keystone fish species and their habitat requirement,
- b) To establish the relationship discharge and hydraulic parameters,
- c) To recommend the environmental flows for keystone fish species.

REVIEW OF LITERATURE

2.1 Evolution and Development of E-Flow Concept

The development of environmental flows assessment (EFA) methodologies began in the USA in the late 1940s, mainly as a result of new environmental and freshwater legislation accompanying the peak of the dam-building era. Australia and South Africa are the other advanced countries with respect to development and application of EFA methodologies (Tharme, 2003).

Several countries have made environmental flows mandatory through various guidelines, such as The Mekong River Agreement, 1995; South Africa's National Water Act, 1998; Swiss Water Protection Act, UNEP Act, etc. The South African Water Act of 1998 stipulates that future water resource developments should be environmentally sustainable and that a component of the natural flow of rivers should be reserved to ensure some level of ecological functioning. Detailed methods for quantifying the environmental instream flow requirements of rivers have been available internationally and in South Africa for some time, but the implementation of the new act introduced a degree of urgency and pointed towards the need for rapid, low-confidence assessments that could be used for initial planning. The desktop reserve model was developed to fulfill this requirement, but since its development in 1999, there have been many more detailed IFR determinations. Initially, the practice of EFR's began as a commitment to ensuring a 'minimum flow' in the river, often arbitrarily fixed at 10% of the mean annual runoff (World Commission on Dams, 2000). However, this 'minimum flow' approach may not be appropriate for safeguarding essential downstream environmental conditions of the river system.

Several methods/methodologies have been proposed in the literature for assessment of environmental flows. These methods range from the simplistic use of the hydrological record to establish minimum and flushing flows to sophisticated procedures linking changes in river discharge with a geomorphological and ecological response. Some methods consider socio-economic aspects also such as DRIFT, BBM. The hydrologic index methods and hydraulic rating methods are based entirely on hydrologic analysis of hydrologic data such as discharge, velocity, depth of flow, wetted perimeter, and wetted area at different cross sections of the river reach. Recent studies have combined a number of methods within

a broader methodological framework designed to provide comprehensive recommendations on water allocations for ecosystem protection.

In several countries, the main objective of EFA has been to define a minimum acceptable flow based on predictions of instream habitat availability matched against the habitat preferences of one or a few species of fish (Jowett, 1997; Pusey, 1998). Since fish species such as trout and salmon are very sensitive to flow, it has been argued that if the flow is appropriate for them, it will probably serve most other ecosystem needs. However, scientific literature reveals that this may not necessarily be so, and flow management is best addressed for the entire ecosystem. Recent EFA methodologies increasingly take a holistic approach (Brown and King, 2003; Instream Flow Council, 2002) as discussed later.

The concept of environmental flow is a rather progressive one. The concept emerged in order to address the larger question of sustainability and the preservation of rivers and associated ecosystems. The concept is very crucial to get an in-depth understanding of the management of water resources. The concept of environmental flow came to light due to the continuous degradation of rivers and ecosystems. The increasing exploitation of water resources has inadvertently had a detrimental effect on societies and economies that are dependent on them. Environmental flow has now moved beyond being a theoretical concept and is now required to salvage deteriorating rivers and water systems.

Before we delve in various methodologies which are used to analyse 'flow', a conceptual understanding and interpretation by various scholars in the field would help bring about a holistic understanding of its uses and possibilities. During the 1950s and 1960s, numerous studies were made on the relationship of fisheries with a variety of stream variables, including channel morphology and river flows (Fausch *et al.*, 1988) and the need for regulating low flows (Wood and Whelan, 1962). During the 1970s and 1980s, the hydropower development projects in the northwest USA came under the examination of regulatory agencies and fisheries management interests at state and federal level.

It was natural that such a narrow objective gives rise to the concept of 'minimum flow'. However, it is interesting to note that the concept of 'minimum flow' was criticized from the very beginning by Stalnaker (Stalnaker and Arnette, 1976) who called it a myth (Stalnaker 1979, 1990). He pointed out that all instream uses for which flows may be needed had not been identified, hence, "most often overlooked are necessary periodic high flows that move bed load, flush sediments, rejuvenate the floodplain, and generally maintain the structural characteristics of a stream channel, which should be maintained in dynamic equilibrium with its watershed".

The discussion soon grew stronger to consider a wide range of issues including riverine habitats, geomorphology, another biota, and water quality. This led to the development of the concept of 'Instream Flow Requirement' and a methodology to cover these aspects (Bovee 1982, Trihey and Stalnaker, 1985).

Dynesius and Nilsson (1994) calculated that 77% of the total discharge of the 139 largest river systems in the North America, Europe and the republics of the former Soviet Union, is strongly or moderately affected by flow-related fragmentation of river channels. Moreover, they observed that large areas in this northern third of the world entirely lack unregulated large rivers.

Over half of the world's accessible surface water is already appropriated by humans, and this is projected to increase to an outstanding 70% by 2025 (Postel *et al.*, 1996; Postel, 1998).

Flow regulation through impoundments represent the most prevalent form of hydrological alteration with, according to most recent estimates, currently, over 45000 (and probably far closer to 48000) large dams in over 140 countries(WCD, 2000); a further 800 000 small dams are estimated to exist worldwide(McCully, 1996).

Reventa *et al.* (1998, 2000) estimated that 60% of the world's rivers are fragmented by hydrologic alteration, with 46% of the 106 primary watersheds modified by the presence of at least one larger dam. In a study of 225 basins throughout the world, (Nilsson *et al.* 2000; Bergkamp *et al.* 2000), found that 83 (37%) and 54 (24%) of rivers basins were highly or moderately fragmented, respectively.

Goyal *et al.* (2001) analyzed that stream flow data to estimate low flow statistics of Tawi River at Jammu. Monthly and annual streamflow characteristics were determined using the average daily discharge data. Maximum, minimum and average flows were determined on monthly basis. Flow duration curves were also plotted, and flows at different probabilities were computed. It was concluded that change in stream flow pattern during last 20 years shows possible impact of climate change as well as of human activities in the catchment.

Tharme (2003) reviewed the present status of environmental flow methodologies worldwide. It revealed the existence of some 207 individual methodologies, recorded for 44 countries within six world regions. These could be differentiated into hydrological, hydraulic rating, habitat simulation, and holistic methodologies, with a further two categories representing combination-type and other approaches. Although historically, the United States has been at the forefront of the development and application of methodologies

for prescribing environmental flows, using 37% of the global pool of techniques, parallel initiatives in other parts of the world have increasingly provided the impetus for significant advances in the field.

Application of methodologies is typically at two or more levels: (1) Reconnaissance-level initiatives relying on hydrological methodologies are the largest group (30% of the global total), applied in all world regions. Commonly, a modified Tennant method or arbitrary low flow indices are adopted, but efforts to enhance the ecological relevance and transferability of techniques across different regions and river types are underway; (2) At more comprehensive scales of assessment, two avenues of application of methodologies exist. In developed countries of the northern hemisphere, particularly, the instream flow incremental methodology (IFIM) or other similarly structured approaches are used. As a group, these methodologies are the second most widely applied worldwide, with emphasis on complex, hydrodynamic habitat modeling. The establishment of holistic methodologies as 8% of the global total within a decade, marks an alternative route by which environmental flow assessment has advanced. Such methodologies, several of which are scenario-based, address the flow requirements of the entire reverse eco-system, based on explicit links between changes in flow regime and the consequences for the biophysical environment. Recent advancements include the consideration of ecosystem-dependent livelihoods and a benchmarking process suitable for evaluating alternative water resource developments at the basin scale, in relatively poorly known systems. Although centered in Australia and South Africa, holistic methodologies have stimulated considerable interest elsewhere. They may be especially appropriate in developing world regions, where environmental flow research is in its infancy and water allocations for ecosystems must, for the time being at least, be based on scant data, best professional judgment and risk assessment.

2.2 E-Flow Assessment (EFA) Methodologies

EFA methodologies have been classified in several ways by different organizations as shown in Table 2.1. The categorization by IWMI is considered more practical as it is based on the required input data and not on the methodological characteristics, which may change over time and be overlapping (Louise, 2006).

Perspective and interactive approaches: Perspective EFAs recommend a single environmental flow. By using this perspective approach, however, insufficient information is supplied on the implications of not providing the recommended flow. Interactive EFAs focus on establishing the relationship between river flow and one or more attributes of the

river system. This relationship may then be used to describe environmental/ecosystem implications (and resulting social/economic implication) of various flow scenarios. Interactive methodologies thus facilitate the exploration of trade-offs of several water allocation options.

Bottom-up and top-down approaches: The basis of most EFA is a bottom-up approach, which is the systematic construction of a modified flow regime from scratch on a month-by-month (or more frequent) and element-by-element basis, where each element represents a well-defined feature of the flow regime intended to achieve particular objectives. In contrast, top-down approaches define the environmental flows requirement in terms of accepted departures from the natural (or another reference) flow regime. Thus, top-down approaches are less susceptible to the omission of critical flow features than bottom-up approaches.

Methods and methodologies: Tharme (2003) distinguished the two levels of EFA as “methods” (procedures or techniques used to measure, describe or predict changes in important physical, chemical or biological variables of the stream environment) and “methodologies” (collection of several instream flow methods which are arranged into an organized iterative process which can be implemented to produce results). The critical review, development and evaluation of these assessment methodologies have been dealt in details by many researchers (Tharme, 1996; Jowett, 1997; Dunbar *et al.*, 1998; Tharme, 2003; Acreman and Dunbar, 2004; Jha *et al.*, 2008, Arthington, 2012, Hartfield *et al.* 2013, Linnansaari *et al.*, 2012).

Table 2.1: Categorization of EFA methodologies

Organization	Category	Sub-category	Example
IUCN (Dyson <i>et al.</i> 2003)	Methods	Look-up Tables	Hydrological (e.g. Q95 index); Ecological (e.g. Tennant Method)
		Desktop Analysis	Hydrological (e.g. Richter Method); Hydraulic (e.g. Wetted Perimeter Method); Ecological
		Functional Analysis	Building Block Methodology (BBM); Expert Panel Assessment Method (EPAM); Benchmarking Methodology
		Habitat Modelling	Physical Habitat Simulation Modelling (PHABSIM)
	Approaches		Expert Team Approach; Stakeholder Approach (expert and non-expert)
	Frameworks		Instream Flow Incremental Methodology (IFIM); Downstream Response to Imposed Flow Transformation (DRIFT); Ecological Limits of Hydrological Alteration (ELOHA)
World Bank (Brown and King, 2003)	Perspective Approaches	Hydrological Index Methods	Tennant Method, Desktop method
		Hydraulic Rating Methods	Wetted Perimeter Method
		Expert Panels	
		Holistic Approaches	Building Block Methodology (BBM)
	Interactive Approaches		Instream Flow Incremental Methodology (IFIM); Downstream Response to Imposed Flow Transformation (DRIFT); Ecological Limits of Hydrological Alteration (ELOHA)
IWMI (Tharme, 2003)	Hydrological Index Methods	Hydrological Index Methods	Tennant Method, Desktop method
		Hydraulic rating Method	Wetted Perimeter Method
		Habitat Simulation Methodologies	Instream Flow Incremental Methodology (IFIM)
		Holistic Methodologies	Holistic Approach; Instream Flow Incremental Methodology (IFIM); Downstream Response to Imposed Flow Transformation (DRIFT); Building Block Methodology (BBM); Expert Panel Assessment Method (EPAM); Scientific Panel Assessment Method (SPAM); Habitat Analysis Method; Ecological Limits of Hydrological Alteration (ELOHA)

2.2.1 Hydrological index methods

These are the simplest and most widespread EFA methods, also referred to as desk-top or look-up table methods. These methods are primarily on historical flow records. An environmental flow is usually given as a percentage of average annual flow or as a percentile from the flow duration curve, on a seasonal or monthly basis. Commonly, the Environmental Flow is represented as a proportion of flow (often termed the ‘minimum flow’, e.g. Q95 – the flow equaled or exceeded 95 percent of the time) intended to maintain river health. Most methods simply define the minimum flow requirement; however, in recognition of the ‘Natural Flow Paradigm’ more sophisticated methods have been developed that take several (up to 32) flow characteristics into account (such as low flow durations, the rate of flood rise/fall etc).

Montana or Tennant Method

Tennant (1976) considered the three factors of wetted width, depth, and velocity as being crucial for fish wellbeing. Tennant (1976) measured variables concerning physical, biological and chemical parameters along 58 transects from 11 different streams at 38 different discharges (a total of 196 miles of stream). These data were gathered in three north-western states of the United States and augmented with additional data collected from a further 21 states. He proposed that certain flows could achieve the maintenance of particular amounts of habitat as given in Table 2.2. Tennant considered biota other than fish in the formulation of these standards but was concerned chiefly with the maintenance of in-stream secondary production and recreational salmonid fisheries. He recognized that the flat allocation of a single discharge to a modified flow regime effectively removed all trace of any pre-existing pattern of seasonality. Therefore, Tennant proposed a series of different flows for two six-month blocks (Table 2.2).

Table 2.2: Proportion of mean annual flow to achieve the maintenance of differing levels of habitat quality

Flow category	Recommended baseflow regime (%)	
	October to March	April to September
Flushing or maximum	200	200
Optimum	60–100	60–100
Outstanding	40	60
Excellent	30	50
Good	20	40

Fair or degrading	10	30
Poor or minimum	10	10
Severe degradation	<10	<10

Tennant (1976) suggested that the method is most applicable for mountain streams with ‘virgin’ flow. If the flow regime is already partly regulated, then suggested allocations may be too low. This method is dependent on the provision of extensive flow data. In many regions of the world, such long-term flow records are not available. Furthermore, where long time series of data are available, care must be taken in choosing which period of record is used as the basis for water allocations. Therefore, the choice of a segment of stream flow data upon which to base an environmental allocation seems critical.

The relationship between habitat suitability and proportions of mean annual flow, which forms the basis of the Montana Method, has not been examined in India. Moreover, in regions with variable flows (i.e. the mean flow is substantially different to the median flow), application of the Montana Method may result in allocations more generous than are required (Richardson, 1986; Tharme, 1996).

The Montana Method has been criticized for offering an assessment of only low to moderate resolution, encompassing limited temporal differences in flow allocations (Stalnaker and Arnette, 1976). In other words, only two ‘seasonal’ flows are possible, The Montana method is generally for baseflows only and has little provision for recommending other ecologically important flows (e.g. spates and floods).

Arthington et al. (1992a) regarded the adoption of 20th, 50th and 80th percentile flows (drought, median and flood flow respectively) as defining the boundary conditions within an environmental flow allocation and, further, that the incorporation of variability within the monthly flow was needed. Incorporation of monthly percentile flows allows the maintenance of the natural temporal pattern of intra-annual variation. Furthermore, additional volumes may also be added to monthly allocations to achieve specific ecological purposes or to accommodate for downstream abstraction or diversion (Arthington *et al.*, 1992a; Swales *et al.*, 1994).

Look-up Tables

France: A Hydrological index is used in France, where the Freshwater Fishing Law (June 1984) required that residual flows in bypassed sections of the river must be 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).

UK: In regulating abstractions in the UK, an index of natural low flow has been employed to define the environmental flow. Q95 (i.e. that flow which is equaled 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 (Barker and Kirmond, 1998).

USA: Tennant (1976) developed a method using calibration data from hundreds of sites on rivers in the mid-western states of the USA to specify minimum flows to protect a healthy river environment. Percentages of the mean flow are specified that provide different quality habitat for fish e.g. 10% for poor quality (survival), 30% for moderate habitat (satisfactory) and 60% for excellent habitat. The indices have been adapted for other climatic regions in North America and have been widely used in planning at the river basin level.

Indices based purely on hydrological data are more readily calculated for any new region, as flow data tend to be generally available. Look up tables do not necessarily take account of site-specific conditions. Therefore these are particularly appropriate for low controversy situations. They also tend to be precautionary. One of the most referred hydrological indexes is 7Q10 (lowest flow recorded for seven consecutive days within a 10-year return period). Although this index is very popular (Tharme 2003; Caissie *et al.* 2007, Richter *et al.* 2011), it does not represent an E-Flow method. Another index 7Q2 was earlier used representing about 33% of the mean annual flow in the rivers in Quebec, Canada (Caissie and El-Jabi 2003). As these indices have no strong scientific basis, the Instream Flow Council has stressed that 7Q10 even may cause several degradations of fisheries (Annear *et al.* 2004). The U.K. Environment Agency has come out with an Environmental Flow Indicator (EFI) as a percentage deviation from the natural flows for different river types and at different flows: low flows (Q95) and flows above Q95 by using flow duration curve (UKTAG 2008).

2.2.2 Desktop methods

Desktop methods can be sub-divided into (a) those based purely on hydrological data, and (b) those that employ both hydrological and ecological data.

a) Desktop methods based on hydrological data

Desktop methods examine the whole river flow regime rather than using simple pre-derived statistics. A fundamental principle is to maintain integrity, natural seasonality, and

variability of flows, including floods and low flows (e.g. drying out where rivers are ephemeral).

(i) The range of variability approach (RVA):

The range of variability Approach developed by Richter *et al.* (1997) uses the indicators of hydrological alteration (IHA) as given in Richter *et al.* (1996). They developed a hydrological method intended for setting benchmark flows on rivers, where protection of the natural ecosystem is the primary objective. Development of the IHA approach concentrated on identification of the components of a natural flow regime, indexed by magnitude (of both high and low flows), timing (indexed by monthly statistics), frequency (number of events), duration (indexed by moving average minima and maxima) and rate of change. The method used gauged or modeled daily flows and a set of 32 indices (Richter *et al.*, 1996). Each index was calculated on an annual basis for each year in the hydrological record and thus concentrates on inter-annual variability in the indices. The question to be addressed is how much deviation from natural ranges of these parameters is too much? Where no ecological information is available to answer this question, the RVA uses a default range of variation based +/-1 standard deviation from the mean or between the 25th and 75th percentiles.

Olden and Poff (2003) observed that only a subset of IHA parameters should be used in any analysis. Black *et al.* (2005) proposed the modification of IHA method and developed the Dundee Hydrological Regime Alteration Method (DHRAM) to be compatible with the requirements of European Commission Water Framework Directive. Further, Gao *et al.* (2009) examined the DHRAM method along with the new concept of seasonal Ecodeficit and Ecosurplus proposed by Vogel *et al.* (2007) and concluded that the three metrics provided a good representation of the degree of alteration of a flow regime and explained most of the variability represented by 32 IHA statistics. Recently, the suitability of Ecodeficit and Ecosurplus has been further checked and verified by Kannan and Jeong (2011). Gopal (2013) also pointed out that IHA or RVA do not recommend any environmental flow values; they are useful tools to assess the changes in flow regimes.

(ii) Desktop Reserve Model (DRM):

Hughes and Munuster (2000) and Hughes and Hannart (2003) developed a desktop method for rivers in South Africa. The user calculates a hydrological index (i.e. coefficient of variation of flows divided by the base flow index; CV/BFI) using river flow data at the site. Then, curves are employed to define the percentages of mean annual runoff (MAR)

volume that is required for different components (low flows and floods) of the environmental flow regime.

BFI is a non-dimensional ratio which is defined as the volume of baseflow divided by the volume of total streamflow (or alternatively, as the ratio between the average discharge under the separated baseflow hydrograph and the average discharge of the total hydrograph). In catchments with high groundwater contribution to streamflow, BFI may be close to 1, but it is equal to zero for ephemeral streams. Some sources list characteristic values of BFI for a number of rivers in certain regions (FRIEND, 1989; Smakhtin and Watkins, 1997). BFI was found to be a good indicator of the effects of geology on low-flows and for that reason is widely used in many regional low-flow studies.

(iii) Flow Duration Curve Based Approach

A flow duration curve (FDC) is a plot of flow vs percentage time equaled or exceeded. This can be prepared using the entire time series data of flow or the flow data pertaining to a specific period (such as a month) in different years. Further, it can be developed for a particular site or combining data for different sites on per unit catchment area basis in a hydrometeorological homogeneous region.

Stalnaker and Arnette (1976) suggested that the use of flow duration curve analysis is problematic unless the hydrological pattern of the stream in question is similar to that of the region for which it was developed. In the United States, several methods have been devised, including the original procedure, which modify flow duration curve analysis to account for such differences in stream size and region (Tharme, 1996).

Flow duration curve analysis does seek to reintroduce some level of seasonality back into the modified flow regime and this is its greatest strength. A major disadvantage, however, is a questionable identification of exactly what flows are necessary to maintain certain aspects of the aquatic environment. In addition, flow duration curve analysis, as it stands, does not explicitly allow for a consideration of inter-annual variation of discharge.

A major assumption of flow duration curve analysis is that the most frequent conditions over a period of record are suitable for all life history stages without any examination of short-duration perturbations and species responses (Richardson, 1986). Moreover, it also assumes that the prolonged imposition of a certain flow has the same ecological effect as a group of repeated but temporally discrete events of the same magnitude. There is little theoretical or empirical basis for these assumptions.

(iv) Environmental Management Class (EMC) based FDC Approach

Smakhtin and Anputhas (2006) reviewed various hydrology based environmental flow assessment methodologies and their applicability in the Indian context. Based on the study, they suggested a flow duration curve based approach which links environmental flow requirement with environmental management classes.

This EFA method is built around a period-of-record FDC and includes several subsequent steps. The first step is the calculation of a representative FDC for each site where the environmental water requirement (EWR) is to be calculated. The sites with observed flow data are referred to as ‘source’ sites. The sites where reference FDC and time series are needed for the EF estimation are referred to as ‘destination’ sites. Typically, the destination site is significantly impacted by upstream basin developments (such as flow diversion). Therefore, representative ‘unregulated’ monthly flow time series, or corresponding aggregated measures of unregulated flow variability, like FDCs, have to be simulated/derived from available observed (source) records.

All FDCs in this approach are represented by a table of flows corresponding to the 17 fixed percentage points: 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99 percent. These points (i) ensure that the entire range of flows is adequately covered, and (ii) easy to use in the context of the following steps. FDC are calculated directly from the observed record or from part of the record which could be considered ‘unregulated’. Normally the earlier part of each record - preceding major dams’ construction – are used to ensure that monthly flow variability, captured by the period-of-record FDC, is not seriously impacted. For each destination site, an FDC table is calculated using a source FDC table from either the nearest or the only available observation flow station upstream.

EF aim to maintain an ecosystem in, or upgrade it to, some prescribed or negotiated condition/status also referred to as “environmental management class (EMC)” have been used in this method. The higher the EMC, the more water will need to be allocated for ecosystem maintenance or conservation and more flow variability will need to be preserved.

Default FDCs representing a summary of EF for each EMC are determined by the lateral shift of the original reference FDC – to the left, along with the probability axis. A linear extrapolation is used to define the ‘new low flows’ at the lower tail of a shifted curve.

An environmental FDC for any EMC only gives a summary of the EF regime acceptable for this EMC. The curve, however, does not reflect the actual flow sequence. At the same time, once such environmental FDC is determined, it is also possible to convert it into the actual environmental monthly flow time series. The spatial interpolation procedure

described in detail by Hughes and Smakhtin (1996) can be used for this purpose. The underlying principle of this technique is that flows occurring simultaneously at sites in reasonably close proximity to each other correspond to similar percentage points on their respective FDCs.

(v) Alberta Desktop Method

Locke and Paul (2011) developed a desktop method based on historical discharge which will protect the riverine environment. The method considered the limited abstraction of water from the rivers by supporting the sustenance of instream and riparian habitats. They recommended the 15% instantaneous reduction from natural flows or the lesser of either the natural flow or the 80% exceedance natural flow on the basis of weekly or monthly discharge data. Hatfield et al. (2013) stressed that the method did not consider the stream size/type and issues of lateral connectivity. Linnansaari *et al.* (2012) also suggested that the percentages of natural flows may vary depending on different river types.

(vi) Sustainability Boundary Approach (SBA)

Ritcher (2010) tried to assess the extent up to which the natural flow regime may be allowed to alter without significantly impacting the ecosystem functions of the river. This approach he termed as Sustainability Boundary Approach. The permissible alteration in the flow regime is assessed by applying some E-Flow assessment methods and in consultation with stakeholders. This approach constrains the hydrological alterations within a percentage-based range around natural flow regime while maintaining the variability of natural flow regime instead of recommending the environmental flow. These boundaries are also reflected in the Ecological Limits of Hydrological Alteration (ELOHA) which have been discussed further in holistic methodologies. As the implementation of ELOHA may be resource intensive and time-consuming, Ritcher *et al.* (2011), as an interim measure, proposed another method called 'Presumptive Standard'. On the basis of their findings, they recommended that "a high level of ecological protection will be provided when daily flow alterations are not greater than 10%; a high level of protection means that the natural structure and function of the riverine ecosystem will be maintained with minimal changes". He further suggested for the higher alterations that "There may be measurable changes in structure and minimum changes in ecosystem functions and alterations greater than 20% will likely result in moderate to major changes".

b) Desktop methods based on hydrological and ecological data

Methods that use ecological data tend to be based on statistical relationships between independent variables such as flow to biotic dependent variables. The latter could be simple,

such as total abundance or species richness, or more complicated matrices calculated from lists of taxa observed in the samples. The advantages of this type of approach are that it directly addresses the two areas of concern (flow and ecology) and takes into account, directly, the nature of the river in question. However, there are some disadvantages:

- (a) It is difficult or impossible to derive biotic indices that are sensitive only to flow and not to other factors (e.g. habitat structure, water quality). Hence, biotic indices designed for water-quality monitoring purposes should be used with great caution (Armitage and Petts, 1992).
- (b) Lack of both hydrological and biological data is often a limiting factor; sometimes routinely collected data may be gathered for other purposes and not be suitable.
- (c) Time series of ecological data may well not be independent, which can violate the assumptions of classical statistical techniques.

A method developed in the UK in this category that involves the use of available ecological data is the Lotic Invertebrate Index for Flow Evaluation (LIFE) (Dunbar *et al.*, 1998). It is designed to be used with routine macro-invertebrate monitoring data. A metric of perceived sensitivity to water velocity scores all recorded UK taxa on a six-point scale. For a sample, the score for each observed taxon is weighted based on its abundance, and mean score per taxon is calculated. The system works with either species or family level data. For monitoring sites where historical time series of flows are known, the relationship between LIFE score and preceding river flow may be analyzed. Moving averages of preceding flow have shown a good relationship with LIFE scores over a range of sites. The exact manner in which LIFE score variation can be used to manage river flows is still to be determined. Nevertheless, the principle is believed to be sound and LIFE has the major advantages of utilizing the data collected by existing bio-monitoring programs so is compatible with the European Water Framework Directive.

2.2.3 Hydraulic rating methods

As discussed above, difficulties exist in relating changes in the flow regime directly to the response of species and communities; hence, approaches have been developed that use habitat for target species as an intermediate step. Within the total environmental niche required by an individual animal or plant living in a river, it is the physical aspects that are affected by changes to the flow regime.

The most obvious physical dimension that can be changed by altered flow regimes is the wetted perimeter area of submerged river bed of the channel. Hydraulic rating methods provide simple indices of available habitat (e.g. wetted perimeter) in a river at a given discharge. Graphs of discharge and wetted perimeter provide a basic tool for environmental flow evaluation. As a rule of thumb, shallow, wide rivers tend to show more sensitivity of their wetted perimeter to changes in flow than do narrow, deep rivers.

Gippel and Stewardson (1998) have highlighted the problems of trying to identify thresholds (critical discharges below which wetted perimeter declines rapidly) that can be used to define environmental flows.

Hydraulic rating methods are based on historical flow records (stage-discharge rating curve) and cross-section data. They model hydraulics as a function of flow and assume links between hydraulics (wetted perimeter, depth, velocity) and habitat availability of target biota. In other words, they use hydraulics as a surrogate for the biota. An environmental flow is given either as a discharge that represents optimal minimum flow, below which habitat is rapidly lost or as the flow producing a fixed percentage reduction in habitat availability. In recent years, hydraulic rating methods have been superseded by Habitat Simulation Methodologies or absorbed within Holistic Methodologies.

Wetted Perimeter Method: The wetted perimeter method (Reiser *et al.*, 1989) is the most commonly applied hydraulic rating method. Environmental flows are determined from a plot of the hydraulic variable(s) against discharge, commonly by identifying curve breakpoints where significant percentage reductions in habitat quality occur with decreases in discharge. It is assumed that ensuring some threshold value of the selected hydraulic parameter at a particular level of altered flow will maintain aquatic biota and thus, ecosystem integrity.

The wetted perimeter or area method has been used in Australia (e.g. Tunbridge, 1988; Tunbridge and Glenane, 1988; Anderson and Morison, 1989) however in these studies, this method was not the sole criterion upon which the environmental flow was ultimately based.

The wetted perimeter or area method usually involves the placement of a single transect per site at a location on the river most responsive to changes in flow. The relationship between wetted perimeter and discharge is then determined from measurements taken at several different stage heights. There are several important assumptions associated with the use of the wetted perimeter or wetted area approach. First, it is assumed that single transects per site are adequate to describe the changes within that site that occur with

changing discharge. Second, since those locations that are most responsive to changes in discharge are riffles, then the focus of the study tends to be on this habitat type. It is assumed, therefore, that consideration of one habitat type only is sufficient to fulfill the requirements of other biotopes or habitat types. Third, the most important assumption is that stream area (or perimeter) is a surrogate for many other factors or processes that determine overall stream health or ecological integrity. When considered together, these inherent assumptions result in a highly simplified perception of the stream environment encompassed within a single variable.

The wetted perimeter or area method is based on a series of observations of changes in stream habitat structure with changing discharge and collectively grouped under the heading of wetted perimeter theory (Stalnaker and Arnette, 1976). In this sense, it is similar to Tennant's (1976) proposal that there are general relationships between habitat quality and some aspect of the flow regime (in this case proportion of the mean annual flow). In wetted perimeter theory, there is an association between wetted perimeter and discharge, wherein wetted perimeter increases rapidly with increasing discharge, from a base level of zero flow and reaches an inflection point, where after increases in wetted perimeter occur much more slowly until bank full stage is reached. This inflection point is taken to represent the optimal discharge. Tunbridge (1988), in a report on the environmental flow needs of freshwater rivers and lakes of south-western Victoria, found that such inflections in the relationship between flow and wetted perimeter were often absent or poorly defined.

Gippel *et al.* (1992) noted that reliance on the maintenance of some identified percentage of 'optimum habitat' at a series of river reaches could result in the situation where it is impossible to simultaneously accommodate each reach because of spatially varying 'optimum' discharges (i.e. a site located downstream of another requiring less water in order to maintain optimum habitat). Poorly developed species-specific habitat requirements will only increase the potential for errors of this type.

Gippel *et al.* (1992) were highly critical of the multiple transect approach employed by Hall (1989, 1990, 1991), Hall and Harrington (1991) and Tunbridge (1980), noting that in all of these studies, measured velocities were not the mean velocity but rather the velocity recorded at 0.1 X depth from the stream bottom. Gippel *et al.* (1992) noted that one of the assumptions in multiple transect analyses is that water velocity (particularly that at 0.1 X depth) rises proportionally with increasing stage height, and also noted that this was unlikely to be so.

Gore and Nestler (1988) suggested that the multiple transect method was prone to error because of the assumed proportional change in some habitat variables with increasing stage height. In addition, Tharme (1996) cautions that the distance between transects and the total number of transects for each stream reach is critical in determining the reliability of estimated changes in habitat structure.

2.2.4 Habitat simulation methodologies

Habitat simulation methodologies are widely used and based on hydrological, hydraulic and biological response data. They model links between discharge, available habitat conditions (including hydraulics) and their suitability to target biota. An environmental flow is predicted from habitat-discharge curves or habitat time and exceedance series.

PHABSIM (Physical Habitat Simulation Model) (Bovee, 1986) is the most commonly applied habitat simulation methodology. Habitat simulation methodologies also make use of hydraulic habitat-discharge relationships but provide more detailed, modeled analyses of both the quantity and suitability of the physical river habitat for the target biota. Thus, environmental flow recommendations are based on the integration of hydrological, hydraulic and biological response data. Flow-related changes in physical microhabitat are modeled in various hydraulic programs, typically using data on depth, velocity, substratum composition and cover; and more recently, complex hydraulic indices (e.g. benthic shear stress), collected at multiple cross-sections within each representative river reach. Simulated information on available habitat is linked with seasonal information on the range of habitat conditions used by target fish or invertebrate species, commonly using habitat suitability index curves (Groshens and Orth 1994). The resultant outputs, in the form of habitat-discharge curves for specific biota, or extended as habitat time and exceedance series, are used to derive optimum environmental flows. The habitat simulation-modelling package PHABSIM (Bovee, 1982; Bovee *et al.*, 1998; Milhous *et al.* 1989; Stalnaker *et al.* 1994), housed within the Instream Flow Incremental Methodology (IFIM), is the pre-eminent modeling platform of this type. The relative strengths and limitations of such methodologies are described in King and Tharme (1994); Tharme (1996); Arthington and Zalucki (1998); Pusey (1998) and they are compared with the other types of approach in Tharme (2003).

As PHABSIM method is primarily meant for microhabitats, a number of efforts were made thereafter to develop methods for mesohabitats and macrohabitats. Parasiewicz (2001, 2007, 2008) came out with a mesohabitat scale (i.e. Channel units, like run, riffle, pool etc.)

MesoHABSIM model. This model combined the system-scale assessment of ecological integrity with physical habitat distribution to simulate habitat changes at catchment scale. The same types of mesoscale models were later developed by Harby *et al.* (2007), Halleraker *et al.* (2007) and Paul and Locke (2009). Some other models in this category are Tiver Hydraulic and Habitat Simulation Model (RHYHABSIM) developed by Jowett (1989) and Riverine Habitat Simulation (RHABSIM) model (an extensive version of PHABSIM) by the U.S. Fish and Wildlife Service in association with Payne (1994). Recently, the developers of all the above models have come together and came up with the new model, System for Environmental Flow Analysis (SEFA). The details of this model are available at <http://www.sefa.co.nz>.

2.3 Application of E-Flows Methods to Indian Rivers

2.3.1 EF assessment for Rampur hydroelectric project

Rampur Hydroelectric Project (RHEP) with an installed capacity of 412 MW is conceived as a tailrace development from the 1500 MW Nathpa Jhakri Hydroelectric Project (NJHEP). Both of these projects are on Satluj River in the Himachal Pradesh state of India. The RHEP is designed to divert $405 \text{ m}^3 \text{ s}^{-1}$ of desalted water of the Satluj River from the tailrace pool of NJHEP through 15 km headrace tunnel to a surface power station near Bael. In the affected stretch of about 23 km from Jhakri to Bael, the major town is Rampur with more than 24 villages on the left bank and 29 villages on the right bank. It is observed that the villagers have very little dependence on the Satluj flows for drinking, irrigation, and other purposes. Most of them depend for water supply from sources other than the Satluj River. There is only limited direct use of water from the river Satluj.

DHI (2006) carried out a study to assess the direct as well as indirect impacts of restricted water flow in Satluj River, particularly during the lean season, on the riverine system, the health, and hygiene of the downstream population, irrigation practice in the downstream and on aesthetics of the river. The study was primarily concentrated on the river stretch between proposed intake structure for RHEP (which is same as the Jhakri tailrace outfall of NJHEP) and the tailrace outlet of RHEP where diverted water of RHEP will again join the river Satluj.

Hydro-dynamic modeling was performed using MIKE 11 software to produce flow velocity profiles in the Satluj River between Nathpa and Bael so as to determine the most favorable flow conditions for flushing of sediments, dilution for BOD load and for the growth of aquatic life. Different scenarios have been simulated with flow releases varying

from $1 \text{ m}^3 \text{ s}^{-1}$ to $10 \text{ m}^3 \text{ s}^{-1}$. In addition, different BOD loads for the tributaries have been used for DO modeling. The scenarios considered BOD loading variation between 5 mg L^{-1} to 8 mg L^{-1} . It has been observed that for BOD loading of 5 mg L^{-1} , the DO levels at no point along stretch even at the release of $1 \text{ m}^3 \text{ s}^{-1}$ goes below 8 mg L^{-1} . The following observations were made:

- The average maximum velocity in the entire reach between Nathpa and Bael villages is of the order of 1.0 m s^{-1} for a release of more than $4 \text{ m}^3 \text{ s}^{-1}$. The velocity goes down as releases are reduced and this may not be a favorable condition for flushing of sediments. For the releases varying from 4 to $10 \text{ m}^3 \text{ s}^{-1}$, the average maximum flow velocity varies from 1.0 to 1.2 m s^{-1} , which is adequate to flush the sediments of the sizes in the range of $0.7 - 0.8 \text{ mm}$. However, in the lean season, assuming there is no release from Nathpa Dam, the flow in Satluj is mainly from tributaries. This water would have lower silt content and hence even lower flow velocities would be sufficient for sediment flushing.
- The DO level between the Nathpa and Bael stretch falls below 8 mg L^{-1} during the lean season, although only at a small stretch near Ganvi (tributary of Satluj River) confluence. But if releases from the dam are maintained at more than $4 \text{ m}^3 \text{ s}^{-1}$, the DO level at no location will fall below 8 mg L^{-1} and it sustains a level of more than 8 mg L^{-1} between Jhakri and Bael village.
- From an aquatic ecological and fisheries point of view, the average velocities are of the order of 0.6 to 1.2 m s^{-1} for discharges between 1 to $10 \text{ m}^3 \text{ s}^{-1}$, which provides a conducive environment for fish habitat and spawning.

Keeping the above in view, minimum suitable releases from the dam above $5 \text{ m}^3 \text{ s}^{-1}$ was recommended. It was also recommended that to ascertain sediment deposition profiles along the entire Satluj stretch between Nathpa to Bael, a two-dimensional modeling may be undertaken.

2.3.2 EF assessment for the Nathpa Jhakri hydropower project

The 1500 MW Nathpa Jhakri Hydroelectric Project (NJHEP) is a river diversion project on the Satluj River in the Himachal Pradesh state of India with a dam near village Nathpa in district Kinnaur and an underground power house near village Jhakri in district Shimla. About $405 \text{ m}^3 \text{ s}^{-1}$ of water is required to harness the installed capacity of the project. During the lean season (November to March), the flow of the river varies from 100 to $150 \text{ m}^3 \text{ s}^{-1}$. This implies that river bed could be dry during the lean season. However, Satluj River

flow is augmented by flow from tributaries joining the river downstream of the dam as well as a baseflow contribution to the river. Still, there may be critical reaches in which altered flows are not able to sustain the riverbed ecology and riparian environment existing prior to implementation of the project.

In this context, Kumar *et al.* (2007) analyzed the hydrological, hydraulic and ecological data to assess the environmental flows in Nathpa - Jhakri reaches of Satluj River. Village level survey suggested that there were negligible direct uses of river water due to highly inaccessible terrain and the river bank, being rocky, does not support much vegetation. However, the river ecosystem has been negatively impacted by flow alterations caused by the dam. Hydrological (river mapping), hydraulic (cross section, water depth, and velocity) and ecological (river bed and bank flora and fauna) characterization in the study reach were carried out through field surveys and analysis. The assessment of the present ecological status of the river was done by field study at selected locations and the reach up to 10.8 km from Nathpa Dam was considered critical. Hydraulic habitat analysis was carried out for assessing the environmental flows.

As the same discharge on different river bed profiles may produce different habitat conditions due to non-uniformity and irregularity in the river bed, parameters such as width/depth ratio of flow, bed submergence and velocity of flow were considered important for determining the habitat of aquatic life.

During the pre-project condition, a major part of river bed used to be in the submerged condition in the lean season. Similar bed submergence in the lean season is not possible due to substantially lower flows during the post-project condition. In the critical reach of first 10.8 km from Nathpa Dam, four sections have been selected for assessing the bed submergence with different releases from Nathpa Dam. Releases from Nathpa Dam starting from $2 \text{ m}^3 \text{ s}^{-1}$ were considered. A favorable velocity from various considerations (silt flushing, DO, aquatic life) was taken as 1.2 m s^{-1} (DHI 2006). For a particular release from Nathpa Dam, the resulting flows at various sections have been arrived at by addition of the flow contribution from the in-between tributaries. Discharge per unit catchment area of Sholding (for left bank snowfed tributaries), Gaanvi (for left bank snowfed tributaries) and Sailan (for rainfed tributaries) streams was used to derive the discharges of other sub-catchments in the Nathpa-Jhakri reach. The lowest flow contribution of the tributaries in the Nathpa-Jhakri reach corresponds to January/February month which are $0.08 \text{ m}^3 \text{ s}^{-1}$, $1.51 \text{ m}^3 \text{ s}^{-1}$ and $2.67 \text{ m}^3 \text{ s}^{-1}$ at sections 2, 3 and 4 respectively. Required flow area is given by the ratio of required discharge/required velocity. Then resulting depth (D), width (W) and W/D

at various sections for various discharges and flow velocity of 1.2 m s^{-1} were estimated. It can be seen that with release of $7 \text{ m}^3 \text{ s}^{-1}$ the resulting flows at various sections ($7, 7.08, 8.59$ and $11.26 \text{ m}^3 \text{ s}^{-1}$) will cause bed submergence of 72.5%, 85.4%, 46.7% and 41.7% at Sections 1, 2, 3 and 4 respectively in the month having lowest flow. This amount of bed submergence appears to be satisfactory in consideration of habitat requirement. Bed submergence will be higher in other months due to higher flows. It was therefore concluded that minimum release from Nathpa Dam may be $7 \text{ m}^3 \text{ s}^{-1}$.

It was further recommended that a more appropriate term for environmental flow or minimum flow is the managed flow as in addition to discharge, we need to prescribe other hydraulic variables also (velocity of flow, flow variability, depth of flow, submerged width of river bed etc.). These are important for aquatic habitat, silt flushing, water quality and aesthetic river condition. Temporary measures such as the creation of pools at 200 m interval by providing small abstractions and adequate connections between isolated pools and flowing channel may be undertaken after every monsoon season and only in the initial 10.8 km reach.

2.3.3 Assessing ef for brahmani and baitarani river systems

The Brahmani and Baitarani River systems are one of the important river systems in India, in which many water resources projects, industries, and development activities are proposed. Jha et al. (2008) evaluated the EF values at different locations of Brahmani and Baitarani River systems. In the study, daily discharge data of eight stations of Brahmani and Baitarani River Systems were used to compute 1-day, 7-day mean and 30-day mean flow duration curves. The results indicate that the flow duration curves are a useful tool for illustrating and evaluating the relationship between the magnitude and frequency of daily stream flow. With the probability of exceedance corresponding to Q95, the FDC corresponding to 7-day mean discharge for 10 years return period (7Q10) was found appropriate as environmental design flow during drought years/low flow periods and FDC corresponding to 7-day mean discharge for 100 years return period (7Q100) was found appropriate as environmental design flow during normal precipitation years.

2.3.4 Assessment of E-Flows for the Upper Ganga basin

WWF-India initiated the Living Ganga Programme (LGP) in 2007 to develop a comprehensive framework for the sustainable management of water and energy in the Ganga basin in the face of climate change. One of the key challenges for the LGP was to

understand the issue of flows or how much water does the river need to sustain its social, cultural and ecological functions, and how can this be determined? The Building Block Methodology (BBM) was selected for E-Flows assessment (WWF, 2012).

The thematic groups dealing with different disciplines (hydrology, fluvial geomorphology, water quality, hydraulics, biodiversity, cultural-spiritual and livelihood) were set up to take care of one component of the study. To characterize the river in its different reaches, homogenous zones were defined based mainly on the changing gradient and consequent geomorphological conditions overlain by the changing land uses and river developments. A sampling site was identified within each zone: Kaudiyala (representing Zone 1 from Gangotri to Rishikesh), Kachla Ghat (representing Zone 3 from Narora to Farrukhabad) and Bithoor (representing Zone 4 from Kannauj to Kanpur). Zone 2, from upstream of Garhmukteshwer to Narora, was selected as a reference zone, where the relatively unaffected conditions could be used as a bench-mark to assess the state of the other three zones. The thematic groups carried out technical evaluations to determine the flow requirements to maintain the river in a desired future state according to specific objectives for each component. They also carried out interviews with diverse stakeholders to capture their needs and aspirations in terms of their livelihoods and spiritual/cultural well-being. Using a consultative process, each thematic group came up with estimates for appropriate flow regimes to meet the specific objectives and requirements of all species, components, and processes in the river during different seasons. The groups responded to the recommendations of the other groups, estimating the effects that the recommended flows would have in mitigating pollution or other water quality issues. Each group worked out flow motivations corresponding to the three scenarios: (i) Flows for maintenance years (normal years, neither too wet nor too dry); (ii) Flows for drought years; and (iii) Flood flows for both maintenance and drought years.

For the River Ganga, it was estimated that the maintenance flows should be equaled or exceeded 70 years out of 100. Drought flows are the lowest that would still provide some habitat and survival conditions (i.e. fish would survive but may not breed that year). So, for long-term EFs, the water volume required would be at maintenance recommendations or higher for 70% of the time, and between drought and maintenance for 30% of the time. The recommended flows were based on the flow indicators chosen by each working group. The recommended flows at each site are expressed as a percentage of the natural Mean Annual Runoff (MAR). In addition to annual MAR percentages, the monthly flows were

extrapolated from natural flow patterns in each zone for the wettest (August) and driest (January) months of the drought and maintenance years.

2.3.5 Assessment of E-Flows for the Yamuna River at Delhi

The Yamuna River is the largest tributary of the Ganga. Originating from the Yamunotri Glacier, it crosses Uttarakhand, Haryana and Uttar Pradesh and passes by Himachal Pradesh and Delhi, before merging with the Ganga at Triveni Sangam, Allahabad. Soni *et al.* (2013) attempted to compute ecological flow that could maintain the health of the Yamuna River at Delhi and all its natural functions. The mean annual flow for the Yamuna in the Delhi stretch is about $13.9 \times 10^9 \text{ m}^3$ (Jha *et al.* 1988). The water abstraction from the Yamuna River for irrigation and drinking water uses upstream of Delhi about $9.5 \times 10^9 \text{ m}^3$ (CPCB 2006). This leaves only a free river flow of about $4.4 \times 10^9 \text{ m}^3$. For the Yamuna, as for most Indian rivers, ~ 80% of the flow (~ $11 \times 10^9 \text{ m}^3$) occurs in the monsoon (July to September) and only 20% ($2.8 \times 10^9 \text{ m}^3$) in the rest of 9 non-monsoon months (Jha *et al.*, 1988, CPCB 2006). Data from the Flood and Irrigation department of Delhi, on monthly release of water from the Wazirabad barrage in Delhi, indicates total release of $3.8 \times 10^9 \text{ m}^3$ in the monsoon and $0.3 \times 10^9 \text{ m}^3$ in the rest of 9 non-monsoon months (Babu *et al.*, 2003).

Soni *et al.* (2013) conducted river flow analysis and determined the hydraulic radius of the flow and by using appropriate roughness coefficients, the Manning velocities for different stages and width sections and the corresponding discharge. The data was used to prepare a scatter plot of total river discharge versus river stage and an appropriate trend line was fitted in the plot. Thus a standard rating curve giving a site-specific stage-discharge relationship was prepared. A plot of river stage versus main river channel flow velocity for high stage flood including peak flow was also prepared to have an insight into relationship between river stage and main river channel flow velocity.

In the non-monsoon period, the average river stage of 207 m AMSL corresponds to a river channel discharge of $19 \text{ m}^3 \text{ s}^{-1}$. As already mentioned, the average monsoon river stage is 1.9 m above the non-monsoon river stage of 207 m AMSL. Hence the average monsoon river stage in the river channel was estimated as 208.9 m AMSL. This corresponds to the main channel river flow velocity of $\sim 1.6 \text{ m s}^{-1}$ in the monsoon period and total river discharge of $507 \text{ m}^3 \text{ s}^{-1}$.

The total present non-monsoon flow in nine months was estimated at $0.44 \times 10^9 \text{ m}^3$ against the non-monsoon virgin flow of Yamuna River in Delhi stretch of $2.8 \times 10^9 \text{ m}^3$. The

present total non-monsoon flow in nine months is $0.44 \times 10^9 \text{ m}^3$, which is 16% of the non-monsoon natural flow of Yamuna River. This is not the ideal non-monsoon flow required for the Delhi stretch of Yamuna River due to large water demands and heavy sewerage load of Delhi city.

The total monsoon flow in the main river channel in three months was estimated at $2.5 \times 10^9 \text{ m}^3$ and in the shoulder areas adjacent to the main channel of Yamuna River it was estimated at $1.5 \times 10^9 \text{ m}^3$. Thus, the present actual monsoon flow of Yamuna River upstream of Wazirabad Barrage was estimated at approximately $4 \times 10^9 \text{ m}^3$, which is approx. 36% of monsoon virgin flows of $11 \times 10^9 \text{ m}^3$.

There is a hierarchy of flows required for a river to perform its several natural functions. In the monsoon season, flow required to transport sediments and in the non-monsoon season flows required to avoid algal choking were considered as the most significant as this amount of flows will be more than the requirement to meet other ecological needs.

Algal Choking

To avoid still water algal growth, a minimum flow velocity of 0.75 ms^{-1} is needed. The non-monsoon flow (9 months) to enable the Yamuna River to attain this objective was estimated to be $1.8 \times 10^9 \text{ m}^3$, whereas the present total non-monsoon flow is just $0.44 \times 10^9 \text{ m}^3$. The estimated desired minimum non-monsoon flow is approximately 60% of estimated non-monsoon virgin flow of $2.8 \times 10^9 \text{ m}^3$ in Yamuna River.

Sediment Transport

The river is heavily silted and at present has a depth of only 0.6 m in the summer. To remove all river bed sediment of diameters up to 1-2 mm (coarse sand to very fine gravel), a monsoon flow larger than 50% ($5.5 \times 10^9 \text{ m}^3$) will be required. A 50% ($5.5 \times 10^9 \text{ m}^3$) monsoon flow can take out particles of diameter up to ~ 1.2 mm. However, when such particles are transported and desilting occurs, the main channel will deepen enhancing the flow velocity. Consequently, even particles of larger size will be transported. It was concluded that at least 50% ($5.5 \times 10^9 \text{ m}^3$) of the virgin monsoon flow of the Yamuna River is the flushing flow required in this stretch. The main finding was that the river needs close to 50-60% of the natural flow to maintain its health. During the monsoon season, 50% of the free flow is needed for efficient sediment transport (to avoid silting the river bed) and during the non-monsoon period, 60% of the free flow is needed to avoid algal choking.

2.3.6 Assessing EF for Kumbh Fair 2013 at Triveni Sangam, Allahabad

A study was undertaken by WWF (2013) to quantify the environmental flows required to maintain a river ecosystem suitable for *Kumbh Mela* (fair) 2013. Kumbh Mela is a bathing festival, which is held at four locations in India. At each place, it is held once every 12 years. The 2013 Kumbh was held at Allahabad in Uttar Pradesh. It was extended over three months and more than 10 million people bathed on the banks of Ganga river (WWF 2013) at Allahabad in this period. It may be noted that for a bathing festival, depth of flow is important. The recommendations for EF, based on Building Block Methodology (King *et al*, 2000), were as follows:

a) Entire duration of Kumbh:

Using the recommended water depth of 1.2 m, a river stage of 73.53 ± 0.11 m was determined for the entire duration of the Kumbh. Corresponding to this stage the estimated flow is $225 \text{ m}^3\text{s}^{-1}$. The estimated water surface width for this stage is 175 m.

b) Special Snan (bath) Days:

Using the recommended water depth of 1.5m, a stage of 73.83 ± 0.11 m was determined for Special snan days (auspicious days when a larger number of people bathe). Corresponding to this stage the estimated flow is $310 \text{ m}^3\text{s}^{-1}$. The estimated water surface width for this stage is 325 m.

2.4 Other Recent Attempts for E-Flow Assessment

Both at national and international levels, a number of academicians and researchers have attempted to assess environmental flows. Some of these have been summarized as follows:

Iyer (2005) has highlighted the importance of in-stream flows in India for different purposes: “Flows are needed for maintain the river regime, making it possible for the river to purify itself, sustaining aquatic life and vegetation, recharging groundwater, supporting livelihoods, facilitating navigation, preserving estuarine conditions, preventing the incursion of salinity, and enabling the river to play its role in the cultural and spiritual lives of the people”. There are several constraints and factors in which India differs from developed countries such as USA, UK, Australia that have been taken a lead in addressing the problem of EFR.

Gupta *et al* (2005) examined a wider concept of environmental water requirements and suggested that it should include the requirements of both terrestrial and aquatic ecosystems. The former would include direct evapotranspiration through forests, wetlands

and other lands, all supporting distinct ecologies, while the latter would then be understood as environmental flows. This is an interesting view given first, that the requirements of terrestrial ecosystems are currently not explicitly considered, and, second, that at present the environmental flow requirements (*EFR*) and environmental water requirements (*EWR*) are normally taken as synonyms (except rare cases when *EWR* is used to denote the total volume of *EFR* – e.g. Smakhtin *et al.* 2004). At the same time, expanding the term *EWR* beyond the requirements of aquatic ecosystems is hardly feasible as it will only add confusion to the already existing terminology. The issues of water requirements of terrestrial ecosystems are not considered in this report.

Mazvimavi *et al.* (2007) assessed the environmental flow requirements for river basin planning in Zimbabwe. They estimate the amount of water that should be reserved for environmental purposes in each of the 151 sub-basins or water management units of Zimbabwe. A desktop hydrological method is used to estimate the environmental flow requirement (*EFR*). The estimated *EFR*s decrease with increasing flow variability, and increase with the increasing contribution of base flows to total flows. The study has established that in order to maintain slightly modified to natural habitats along rivers, the *EFR* should be 30-60% of Mean Annual Runoff (*MAR*) in regions with perennial rivers, while this is 20-30% in the dry parts of the country with rivers, which only flow during the wet season. The inclusion of *EFR*s in water resources management plans will not drastically change the proportion of the available water allocated to water permits since the amount of water allocated to water permit holders is less than 50% of the *MAR* on 77% of the sub-basins in the country.

Alcazar Jorge *et.al.* (2007) carried out in their study is that Environmental flow estimation in regulated rivers has become a major issue for watershed management in Mediterranean countries. There are many methodologies for environmental flow computation, but they usually require accurate hydrological long-term flow records, which sometimes are unavailable, and/or extensive field measurement campaigns, which can be very costly especially when the environmental flows must be determined at many locations in large basins. We analyzed the potential of neural network models for the estimation of environmental flow values in gauging sections and reaches under a natural flow regime in the watershed of the Ebro River, Spain, with a view to a future application in both ungauged and/or regime-altered sections. Non-linear multilayer feed-forward cascade-correlation neural networks were developed to model the relationships between known environmental flows (Q_b calculated) and two sets of independent variables related to physical and

hydrological watershed characteristics or to the general flow regime. Three models were found capable of good estimations of environmental flows, based on variables such as the 10-year average of the lower monthly flows, the mean value of the length of the period in days with flows continually below the 40% of the mean annual flow (spell duration), and the flow equaled or exceeded 270 days per year (Q270). Correlation coefficients (r) between calculated and estimated values were high (>0.90), and average absolute errors were low (<0.44 m³/s) for the three models. The limited number of variables in the models (just two) was considered very promising for operational application of the model to ungauged or regime-altered sections. Results suggest that artificial neural network models can be simple, robust, reliable and cost-efficient tools for environmental flow determination at the watershed level

Kashaigali *et al.* (2007) presented the finding of a hydrological study conducted to estimate environmental flow requirements. Desktop reserve model (DRM) used for determination of high and low flows, and dry season low flow needs within the Ruaha National Park. The results indicate that to maintain the basic ecological functioning of the river requires an average allocation of 635.3 Mm³/a (equivalent to 21.6% of mean annual runoff). This is the average annual maintenance flow; comprising of maintenance low flows (i.e. 15.9% MAR; 465 Mm³/a) and maintenance high flows (i.e. 5.8% MAR; 170 Mm³/a). The absolute minimum water requirement was estimated to be 0.54 m³/sec with the probability of exceedance of 0.99. This study signifies that in the unavailability of significant ecological information hydrological indices can be used to provide a first estimate of environmental water requirements. However, before being applied, a greater understanding of the relationship between flow and the ecological condition of the riverine ecosystem is required.

Yang *et al.* (2008) carried out an assessment of environmental flow requirement for integrated water resources allocation in the Yellow River Basin. Based on the classification and regionalization of the ecosystem, multiple ecological management objectives and the spatial variability of the environmental flow requirement of the Yellow River Basin were analyzed in this study. The summation rule was used to calculate water consumption requirements and the compatibility rule, i.e. “maximum” principle, was also adopted to estimate the non-consumptive use of water in the river basin. The environmental flows Requirements for integrated resources allocation were determined by identifying the natural and artificial water consumption in the Yellow River Basin. The results indicated that the annual minimum environmental flow requirements amounted to 317.62×10^8 m³, which

represented 54.76 % of the natural river flows, while for the environmental flow requirements for the integrated water resources allocation were $262.47 \times 10^8 \text{ m}^3$, which represented 45.25% of the natural river flows. It can be concluded that the primary concerns should be put on the downstream river water requirements to determine the environmental flows for integrated water resources allocation in a river basin.

In order to provide an integrated assessment of the suitability of environmental flows to safeguard downstream ecosystems and services, Shofiul Islam (2008) presented a methodology which deals on a human being, river functions and their relation with river flow based on an Asian environment. He describes an analytical framework for assessing the relationship between group of people and the river flow regime, in order to determine flow requirements from people perspectives. The near absence of such methods represents a serious gap in the field of Environmental Flow Requirements. It is clear that environmental flow ensures ecosystem sustainability which provides better services to the human well being.

Smakhtin and Erivagama (2008) described a method and software package for desktop assessment of environmental flows- a hydrological regime designed to maintain a river in some agreed ecological condition. The method uses monthly flow data and is built on a flow duration curve, which ensures that elements of natural flow variability are preserved in the estimated environmental flow time series. The curve is calculated for several categories of aquatic ecosystem protection- from 'largely natural' to 'severely modified' category. The corresponding environmental flows progressively reduce the decreasing level of ecosystem protection, calculate the associated environmental flow duration curves and time series and display both. The analysis can be carried out either using default (simulated) global flow data, with a spatial resolution of 0.5 degrees, or a user defined file. The package is seen as a training tool for water practitioners, policymakers and students, and as a tool for period preliminary environmental flow assessment.

Gupta and Das (2008) stressed that consideration of environmental flows in river basin management poses great challenges. Environmental flows are interpreted as the natural or regulated releases of water needed in a river to maintain specified valued features of the river ecosystems. This has never been considered explicitly in water resources management of a river basin. An attempt is, therefore, made here to reflect the perception and implications of environmental flows in water resources management. Assessment approaches are reviewed in the context of flow characteristics of a river system and

recommendations are put forward on what is to be done to adopt this new concept in practice.

Mathew *et al.* (2009) carried out a study to estimate the environmental flow requirements downstream of the Chara Chara weir. The Desktop Reserve Model (DRM) was used to determine both high and low flow requirements in the reach containing the fall. The results indicate that to maintain the basic ecological functioning in this reach requires an average annual allocation of 862 Mm³ (i.e. equivalent to 22% of the mean annual flow). Under natural conditions, there was a considerable seasonal variation, but the absolute minimum mean monthly allocation, even in dry years, should not be less than approximately 10 Mm³. These estimates make no allowance for maintaining the aesthetic quality of the fall, which is popular with tourists. The study demonstrated that, in the absence of ecological information, hydrological indices can be used to provide a preliminary estimate of environmental flow requirements. However, to ensure proper management, much greater understanding of the relationships between flow and the condition of the river ecosystem is needed.

Metcalf (2009) carried out E-Flow assessment for a Complex ecosystems, such as the Upper Mississippi River (UMR), present major management challenges. When no single entity has the knowledge or authority to resolve conflicts over shared resource use, stakeholders may struggle to jointly understand the scope of the problem and to reach reasonable compromises. They described a workshop structure used to engage UMR stakeholders that may be extended to resource use conflicts in other complex ecosystems. They provided recommendations for improving on these participatory methods in structuring future efforts. In conclusion, we suggest that tools which facilitate collaborative learning, such as mediated modelling, need to be incorporated at an institutional level as a vital element of integrated ecosystem management. As an application of mediated modelling, this experience supports.

Richter (2009) highlighted that environmental flows are understood by most of the people as serving only those who like to fish or biodiversity advocates. Misperception of environmental flows is intended that EF is basically beneficial for nonhuman species, in most of the countries EF is limited to regulatory actions for saving endangered species. In issue two uncoordinated management of water resources is discussed, many currently water management programs have conflict in the implementation of EF also regulation of surface water, groundwater and dams and other projects are not well coordinated. Unregulated use of water resources results in the conflicts in EF implementation. The third issue emphasizes

on the low priority given to the EF in allocation systems and in the 5th issue EF limited to generally low flow is discussed. Fifth and six issues discuss about the problems generated by the release of stored water unnaturally in downstream and complex environmental flow specifications. Environmental flows should be considered as an integral part of integrated water management not only as an allocation tool.

Jain (2012) emphasized that EFs for a given river range from relatively simple, low-confidence, desktop approaches to resource-intensive, high-confidence approaches. The most useful and appropriate indicators for assessing river ecosystem integrity over time. Many other abiotic characteristics of riverine ecosystems such as dissolved oxygen content, water temperature, suspended and bed-load sediment size and channel bed stability vary with flow conditions.

The requirement of Environmental Flow approaches using Hydrological Index methods was carried by Dubey (2013) to estimate that the Narmada is the largest west-flowing peninsular river ranks seventh in India in terms of water discharge. A number of dams have been constructed on the Narmada River and its tributaries. As such need arises to regulate the reservoirs for releasing the adequate water in the river throughout the year for maintaining the downstream ecosystem as well as a flushing flow once in a year to ensure regeneration of fish and other species in the river or flood plains. According, it is essential to estimate environmental flow for this river. In this paper, the environmental flow requirement at 4 gauging sites selected at upper parts of Narmada River has been carried out using Lookup Tables, Tennant method. Modified Tennant Method is found to be preferred to estimate the environmental flow requirements, which is more acceptable for allocating EFR on monthly basis. Further, intensive investigations would be necessary to obtain data on ecological needs of the river in order to recommend the realistic values of EFR for this river.

Kanchan *et al.* (2013) underlined that water is one of the most important natural resources for life. Increased urbanization and unplanned infrastructure have deteriorated the water quality as well as quantity of the river. Huge quantities of untreated sewage continuously passing in it has drastically disturbed the local ecosystem, and greatly deteriorated the minimum flow. Thus, this makes environmental flow assessment and management to be taken up at priority. The present recommends and provisions the development of a building-block methodology assisted knowledge-based system for e-flow assessment and management for Suswa river of Dehradun district. The building block methodology works on the principle of drawing post-analysis recommendations from

specialist groups such as hydrologists, geo-morphologists, water quality experts, sociologists, environmentalists and information technology experts.

Assessment of Environmental Flow for a river in Southern India using Hydrological Index Methods was studied by Durbude *et al.* (2014) is that Assessment of E-Flows is emerging trends and new practices, especially in developing countries like India. The river Cauvery, one of the important east flowing rivers of Southern India is having a lot of potential for the development of hydropower projects to satisfy the present demand of power in the state of Karnataka. The e-flows assessment (EFA) method used in various countries such as France, USA, and UK are area specific and the same may not suitable for Indian condition. Hence, the e-flows have been assessed using hydrological index methods such as Look- up Tables, EMC-FDC approach, Tennant and Modified Tennant Method, etc. The range of minimum and maximum values of flow computed using these methods were recommended as e- flows with the remarks that the minimum values should be ensured at any condition to avoid further degradation of the river ecosystem.

Bhattacharjee and Jha (2014) carried out a critical evaluation on the applicability of existing approaches for environmental flow assessment for Mahanadi river basin based on the Tennant method and Range of Variability Analysis (RVA) is made. Tennant (or Montana) method uses a percentage of the Mean annual Flow (MAF) for two different six-month periods to define conditions of flow, whereas RVA uses IHA (Indicators of hydrologic Alterations) applications, to determine low flow, high flow, maximum high flow etc. The Low discharge and the High discharge are computed for the various seasons to maintain an unrestricted flow (Aviral Dhara) over the entire river basin, both along its upstream and downstream. E-Flow assessment is done to understand the natural flow regime of the river which is required to exist for the sustainability of the ecosystem.

Verma *et al* (2015) stressed that Environmental Flows (EFs) assessment is a global challenge involving a number of tangible and intangible segments of hydrology, hydraulics, biology, ecology, environment, socio-economics, and several other branches of engineering including the management of water resources. In this study EFs variability was assessed using hydrological methods. Thus hydrological methods gave results that were in agreement with each other, but in other cases different approaches yielded different results and threshold values.

Rahman *et al.* (2015) presented the finding in their research “Environmental Flow Characteristics of the Gorai River, Bangladesh” in which Environmental flow provides ecological health status of the river. The objective of this research is to determine E-Flow

of Gorai River and to check flow nature of river through which the comparison between past and present time. Mean daily discharge data and mean daily water level data reported by Bangladesh Water Development Board is being possessed and evaluated for two duration i.e. G1 (1976-1990) and G2 (1991-2006). Mean Annual Flow (MAF), Flow Duration Curve (FDC) and Constant Yield (CY) methods have been used and IHA software (version 7.1) has been exercised. According to MAF, FDC and CY methods, environmental flows are estimated as 229.6cms, 230.5cms, and 241.2 cms respectively and averaging these value: e-flow is predicted 233.8cms which report poor flow reports remains from December to May. Mean Annual Flow decreases about 21.8% from G1 to G2 duration where August is highest and April is lowest flowing months respectively for the both periods. Range of Variability methods analysis is being found that very high reduction in flow occurs in month of July whereas high reduction occurs in January, October and December comparing flows between G1 to G2 durations.

Singh, A. K. (2016) examined ecological streams appraisal of Tawi River and suggested Modified Tennant strategy and Building Block Method to ascertain the natural stream necessity of waterways.

Brij Gopal (2016) opined the assessment of E-Flows on the basis of a change in total ecosystem services and their total economic value with the alteration of flow regimes. Such an assessment would consider the gain and loss of ecosystem services both upstream and downstream of the point of intervention which alters the flow regime. It is also proposed that the economic valuation should provide for appropriate weightages to ecosystem services with a strong social, cultural and livelihood bearing in regional/local context.

Johnson *et al.* (2017) carried out E-Flow assessment across the Godavari river basin using physical habitat simulation model (PHABSIM). This model uses habitat requirement of selected fish species in the form of habitat suitability curves (HSCs) against river habitat availability. This estimated volume is similar to the flow suggested on the basis of environmental management class (EMC) of the Godavari river.

Tatea *et al.* (2017) carried out Environmental Flows (E-Flows) assessment in the upper stretches of the Ganga river by integrating ecological and geomorphological parameters with hydraulic analysis to estimate the flow depths and flow volumes necessary for river ecology and channel maintenance. They used a modified version of Building Block Method (BBM) for computing E-Flows for lean period, for monsoon period and for high floods based on the flow requirements of keystone species for different sites and geomorphic considerations. Estimates for all stations fall within 20–50% of mean annual runoff (MAR)

and are less than the minimum natural flows. Our analysis shows unnatural high flows during the dry period. Moreover, the present flows are significantly less than the natural flows during the wet period at most E-Flows sites although they are higher than the E-Flows. This indicates that although the bare minimum eco-geomorphological conditions are being fulfilled.

Akter (2018) highlighted that due to shortage of flow monitoring data in ungauged semidiurnal river, 'environmental flow' (EF) determination based on its key component 'minimum low flow' is always difficult. E- flow threshold establishment faces challenges in changing ecological paradigms with periodic change of tides and hydrologic alterations. Study describes a novel approach through modelling framework comprising hydrological, hydrodynamic and habitat simulation model. This EF assessment was carried with a modelling framework comprised of hydrological, hydraulic and habitat models those are commonly used for water management. The model framework can be applied in both unidirectional and tidal river after calibration and validation.

Hamed Moftakhari *et al.* (2019) suggested a method to link bivariate statistical analysis and hydrodynamic modelling for flood hazard estimation in tidal channels and estuaries is presented and discussed for the general case where flood hazards are linked to upstream riverine discharge Q and downstream ocean level, H . Using a bivariate approach, there are many possible combinations of Q and H that jointly reflect a specific return period, T , raising questions about the best choice as boundary forcing in a hydrodynamic model. Bivariate statistical analysis is introduced to create combinations of river discharge and ocean levels suited for hydrodynamic modelling, and extreme water levels produced by hydrodynamic models are synthesized to create a composite water surface profile representative of return period T .

Mika Marttunen (2019) Environmental monitoring covers many different management domains. They range from biodiversity conservation to water protection, natural hazard prevention, impact assessment, resource use, or environmental restoration. for clear objectives has long been emphasized in the management literature, but has often received only little attention in monitoring design. They presented a formal approach based on Multi-Criteria Decision Analysis (MCDA) and applied the approach only to one restoration measure, namely river widening.

MATERIALS AND METHODS

3.1 Study Area

3.1.1 Origin and location

The river Godavari, the largest of the peninsular rivers, and third largest in India. It's origin in the Western Ghats of central India near Nashik Trimbakeshwar in Maharashtra. It flows east for 1,465 kilometres (910 mi) draining the states of Maharashtra (48.6%), Telangana (18.8%), Andhra Pradesh (4.5%), Chhattisgarh (10.9%), Odisha (5.7%), Karnataka (1.4%), and addition to smaller parts in Madhya Pradesh, and Union territory of Puducherry having a total area of 3,12,812 Sq.km with a maximum length and width of about 995 km and 583 km. It lies between 73°24' to 83°4' east longitudes and 16°19' to 22°34' north latitudes and accounts for nearly 10% of the total geographical area of the country. Emptying into Bay of Bengal through its extensive network of tributaries. The location map of the study area is shown as Fig 3.1.

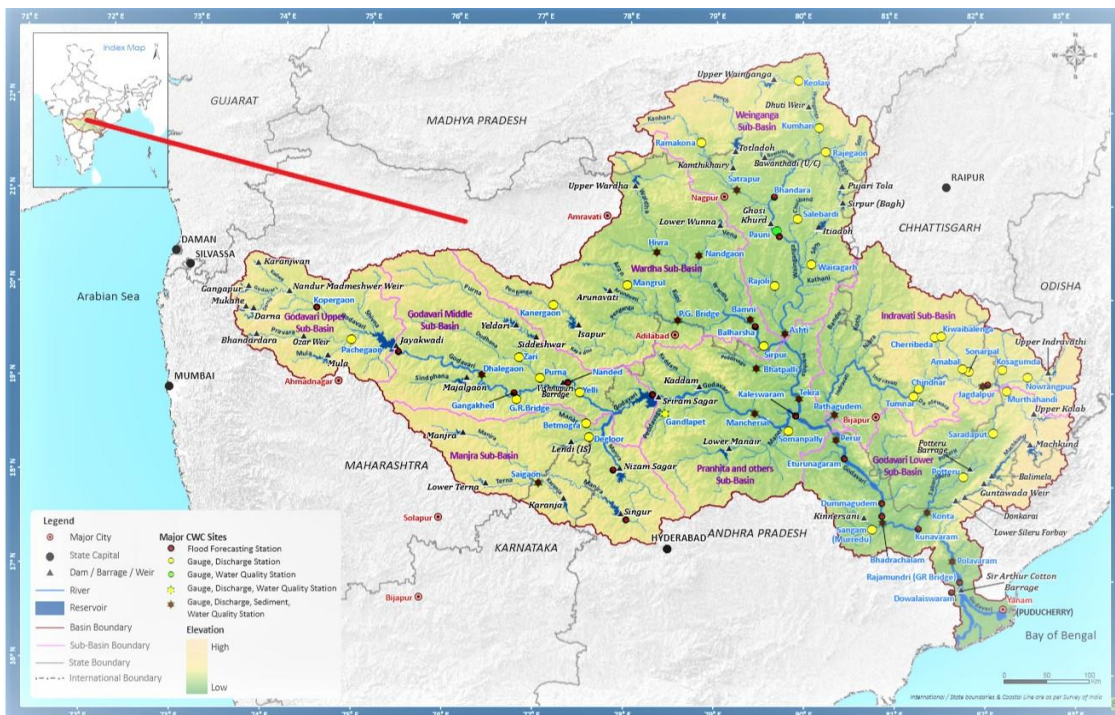


Fig. 3.1: Map of Godavari basin (Source: INDIA-WRIS)

3.1.2 Rainfall

The Godavari basin receives its maximum rainfall during the Southwest monsoon. The monsoon currents strike the West Coast of the peninsula from West and South-West, meet the Western Ghats or Sahyadri Range which present almost an uninterrupted barrier ranging from 600 m to 2100 m in height. The Godavari receives the drainage from a length of about 129 km of the high rainfall zone in the Western Ghats. The annual rainfall varies from 1,000 to 3,000 mm in this reach. East of the western Ghats, the rainfall decreases rapidly to less than 600 mm. There is a belt some distance East of the Western Ghats and in width varying from about 80 km. in the South to about 97 km in the North with less than 600 mm, of normal annual rainfall. The belt which is about 10,360 sq. km. in area, includes portions of Aurangabad and Ahmednagar districts of Maharashtra. After this area the rainfall again gradually increases to about 900 mm towards the East coast. All parts of the basin receive the maximum rainfall in the period from June to September. The Godavari basin as a whole receives 84% of the annual rainfall on an average, during the Southwest monsoon, which sets in mid. June and ends by mid. October. The Indravati and Pranhita sub-basins receive upto 86% and 88% of the annual rainfall during the same period due to influence of the cyclonic storms which predominantly pass through these sub-basins.

3.1.3 Topography

The Godavari basin is bounded on the north by the Satmala hills, on the south by the Ajanta range and the Mahadeo hills, on the east by the Eastern Ghats and on the west by the Western Ghats (600 to 2,100m height). Except for the hills forming the watershed around the basin, the entire drainage basin of the river comprises rolling and undulating country – a series of ridges and valleys interspersed with low hill ranges.

3.1.4 Type of soil

Soil is one of the major natural resources, like air and water. It is the topmost layer of the earth's crust and is a mixture of fine powdered rocks, organic matter, liquids, myriad organisms and other minerals. It acts as an interface between hydrosphere, lithosphere, earth's atmosphere and biosphere. The proportion of the key ingredients determines the type of soil. But, factors such as vegetation, climatic conditions, human activities for e.g. grazing, farming, gardening etc also influence soil formation. In Godavari river basin major soil are black, red and alluvial soil are found.

3.1.4.1 Black soil:

Black soil is also known as black cotton soil as cotton is an important crop which is grown in this type of soil. This soil rich in calcium, carbonate, potash, lime and magnesium carbonate but has poor phosphorus content. Black soil is extremely fine and clayed and has the capacity to hold a lot of moisture. Black soil is good for producing cotton, oilseeds, wheat, linseed, millets, and tobacco.

3.1.4.2 Red soil:

The red soil becomes in a high percentage of iron content. The soil texture varies from being sandy to clay, but it is mainly loam. It is in potash content but lacks phosphate, humus and nitrogen content. The red soil is found in regions such as Tamil Nadu, Madhya Pradesh, Jharkhand, Odisha, some parts of Karnataka and southeast Maharashtra.

3.1.4.3 Alluvial soil:

Alluvial soils are formed by the deposits of the sediments brought by river. The soil is made up of particles like silt, sand and clay. It has adequate amount of phosphoric acid, potash and lime. Alluvial soil is of two types-(1) old alluvium known as bangar and (2) new alluvium called khaddar. It is the most important type of soil found in the country as it covers about 40% of the total land. It is found in deltas of Godavari basin and different river basin such as Krishna, Kaveri, Mahanadi in peninsular India. Alluvial soil is highly fertile and is light grey in colour. Crops mainly wheat, rice, maize, sugarcane, pulses, oilseed etc.

3.1.5 Tributaries

The Godavari river basin major tributaries are the river Pranhita, conveying the combined waters of Penganga, the Wardha and Wainganga, which drain Nagpur and southern slopes of the Satpura ranges, falls into Godavari about 306 km. The largest tributary of the Godavari is the Pranhita with about 34.87% coverage of drainage area. The Pravara, Manjira and Maner are right bank tributaries covering about 16.14%, the Purna, Pranhita, Indravathi and Sabari are important left bank tributaries, covering nearly 59.7% of the total catchment area of the basin. The Godavari in the upper, middle, and lower reaches make up for the balance 24.16%. The particulars of the catchment area, length, elevation of the source points of the river and its tributaries in the order of their occurrence along the length of the main river are indicated in the Table 3.1.

Table 3.1: Major tributaries in Godavari basin

S.No	Name of the river	Elevation of source (m)	Length of tributary (km)	Catchment area (sq. km)	Average annual rainfall (mm)
1.	Upper Godavari	1067	675	33502	770
2.	Pravara	1050	208	6537	606
3.	Purna	838	373	15579	797
4.	Manjira	823	724	30844	846
5.	Middle Godavari	323	328	17205	955
6.	Maner	533	225	13106	932
7.	Penganga	686	676	23898	960
8.	Wardha	777	483	24087	1055
9.	Pranhita	640	721	61093	1363
10.	Lower Godavari	107	462	24869	1208
11.	Indravati	914	535	41665	1588
12.	Sabari	1372	418	20427	1433

3.1.6 Water Resource Development

The water resources potential in Godavari basin has been assessed to be 110.54 km³. The utilisable surface water is about 76.3 km³, the replenishable ground water is about 45 km³. There is a vast potential for irrigation development and hydropower generation in the basin. Prior to Independence only a few irrigation projects were constructed in Godavari basin.

3.1.6.1 Hydropower stations:

The Godavari River is a major waterway in central India. It is known as Dakshin Ganga. The project wise generation data of large hydro with installed capacity of the Godavari basin is given in Table 3.2 and Fig. 3.2.

Table 3.2: Hydropower stations in Godavari basin

S. No	Name of project	Power capacity (MW)
1.	Upper indravati	600
2.	Machkund	120
3.	Balimela	510
4.	Upper silera	240
5.	Lower silera	460

6.	Ghat pumped storage	250
7.	Polavaram	960
8.	Pench	160
9.	Upper kolab	320

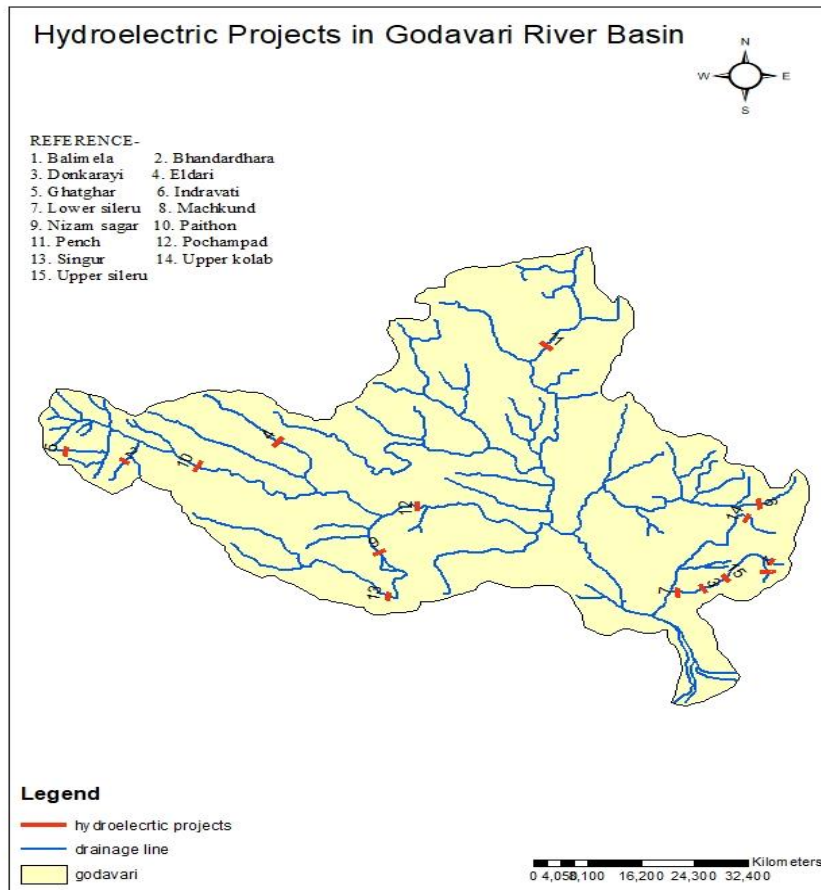


Fig. 3.2: Hydroelectric projects in Godavari river basin

3.1.6.2 Irrigation projects:

The Godavari river has its catchment area extend in seven states (Maharashtra, Telangana, Chhattisgarh, Madhya Pradesh, Andhra Pradesh, Karnataka and Odisha) of India. The number of dams constructed in Godavari basin is the highest among all the river basins in India. Nearly 350 major and medium dams and barrages had been constructed in the river basin.

3.1.6.3 Hydrological observation: Hydrological observation sites in Godavari river basin are shown in Fig. 3.3.



(Source: INDIA-WRIS)

Fig. 3.3: Hydrological observation sites in Godavari river basin

3.1.7 Ecological concern

The Godavari river has a frequent drying up in the drier months has been a matter of great concern. Indiscriminate damming along the river has been cited as an obvious reason. This had hit the growth of fish, making the life of fishermen miserable. The water-level was so low that people could easily walk into the middle of the river. Further epitomise the insensitivity towards Godavari river basin Project which is touted to be large— both in terms of size and violations. Deemed as being pointless and politically driven, the project raises questions about environmental clearance, displacement of upstream human habitations, loss of forest cover, technicalities in the dam design which are said to play down flood threats and unsafe embankments.

High alkalinity water is discharged from the ash dump areas of many coal fired power stations into the river which further increases the alkalinity of the river water whose water is naturally of high alkalinity since the river basin is draining vast area of basalt formations. This problem aggravates during the lean flow months in entire river basin. Already the Godavari basin area in Telangana is suffering from high alkalinity and salinity water

problem which is converting soils in to unproductive sodic alkali soils. The following are the few coal fired power stations located in the river basin.

3.2 Data Used for the Present Study

The daily discharge data for Godavari basin at Satrapur site for the period of 1 June 1987 to 31 May 2017 was downloaded from INDIA-WRIS website. The cross sections at Satarpur site have also been obtained from INDIA-WRIS website. The Landsat-8 data of 4 May 2015 of digital elevation model was obtained from USGS site.

3.3 Methodology

Since the mid-1970s, there has been a quick expansion of techniques for evaluating natural stream for a given waterway, extending from generally straightforward, low-certainty, work area approaches, to asset serious, high-certainty approaches (Tharme, 2003). The complete strategies depend on definite multi-disciplinary examinations that frequently include master exchanges and accumulation of a lot of geomorphologic and biological information (for example Ruler and Louw, 1998). Normally they take numerous months, once in a while year, to finish. A key imperative to the use of exhaustive techniques, in numerous nations, is the absence of information connecting biological conditions to explicit streams. To make up for this, few strategies for assessing natural streams have been built up that depend exclusively on hydrological files got from verifiable information (Tharme, 2003). Despite the fact that it is perceived that a heap of components impact the biology of amphibian biological systems (for example temperature, water quality and turbidity), the regular supposition of these methodologies is that the stream routine is the essential main thrust (Richter et al., 1997).

In excess of 200 strategies are utilized to recommend waterway streams expected to keep up solid waterways in world. There has been a progressive evolution of methodologies for assessing the Environmental Flow Assessment of riverine ecosystem. The focus of environmental flow assessment is on the maintenance of economically important freshwater, the channel from, sediment transport, water quality, aquatic life, riparian vegetation, and floodplain wetlands including nutrient cycling and primary production. Such far reaching methodologies incorporate Float (Downstream Reaction to Forced Stream Change), BBM (Building Square Strategy), and the "Savannah Procedure for site-explicit natural stream appraisal, and ELOHA (Biological Points of confinement of Hydrologic Adjustment) for territorial scale water asset arranging and the board. The "best" technique,

or almost certain strategy for a given circumstance relies upon the measure of assets and information accessible, the most significant issues, and the dimension of assurance required. To encourage ecological stream medicines, various PC models and apparatuses have been made by gatherings, for example, the USACE's Hydrologic Building focus to catch stream prerequisites characterized in a workshop setting (e.g., HEC-RPT) or to assess the ramifications of natural stream execution (e.g., HEC-Res SIM, HEC-RAS and HEC-EFM). Furthermore, a 2D model is created from a 3D disturbance model dependent on Smagorinsky huge vortex conclusion to all the more properly model natural huge scale streams. This model depends on a moderate complex of the fierce Smagorinsky enormous whirlpool conclusion rather than traditional profundity averaging stream conditions. The last couple of decades has seen the evolution of various methods, approaches, and frameworks for estimating environmental flows. 'Methods' typically deal with specific assessments of the ecological requirement. 'Approaches' are ways of working to derive the assessments, e.g. through expert panel assessment method (EPAM), Scientific panel assessment method (SPAM). 'Frameworks' for flow management provide a broader strategy for environmental flow assessment.

3.3.1 Probability analysis

Weibull formula method is one of the most descriptive method of exhibiting the complete range of river discharges from high flow to low flow (flood) events. It is a relationship between any given discharge value and the percentage of time that this discharge is equaled or exceeded, or we can say in other words that are the relationship between magnitude and frequency of stream flows discharges.

M = order of event, N = total number of events.

Probability, $P = M / (N+1)$

The flows corresponding to desired return probability (or period) Q90 (dry year), Q50(normal year) and Q10(wet year) was read from calculated values.

Q10 = discharge corresponding to 10% exceedance probability

Q50 = discharge corresponding to 50% exceedance probability

Q90 = discharge corresponding to 90% exceedance probability

3.3.2 Assessment of environmental flows for the reach of Godavari river at Satrapur

To assess the environmental flows, a combination of hydraulic rating methodologies and habitat simulations have been used. The primary reason for applying this method is its

objectivity, availability of data including river cross-sections and better applicability to quantify the environmental flow in a scientific manner. At first, the dry, normal and wet years have been identified through probability analysis. Further, environmental flow regime has been worked out keeping annual occurrence of following main seasons in this region:

Season I: It is considered as high flow season influenced by monsoon. It covers the months from June to September. These 4 months have been considered as monsoon season.

Season II: This season is considered as average flow period, covers the months from October to January. These months have been considered as winter season.

Season III: This season is considered as low or lean or dry flow season which covers the months from February to May. These months have been considered as summer season.

In order to get the representative quantification of environmental flow for the above mentioned three seasons, the water profile simulations on surveyed river cross sections have been carried out at Satrapur, using one dimensional hydrodynamic model HEC-RAS (1D) to estimate the depth of flow, velocity, wetted perimeter, flow area and top flow width for different quantities of flow.

3.3.3 Hydrodynamic simulations using HEC-RAS

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) software developed by U.S. army corps (1995) of Engineers river analysis system. This software allows to perform one-dimensional steady flow, one and two-dimensional unsteady flow, sediment transport calculations, and water quality computations. The HEC-RAS modelling system was developed as a part of the projects encompasses several aspects of hydrologic engineering (rainfall, runoff, river hydraulic, reservoir system simulation, flood damage analysis and river forecasting for reservoir operations). The flow chart showing HEC-RAS steps is given as Fig. 3.4. All the components use a common geometric data.

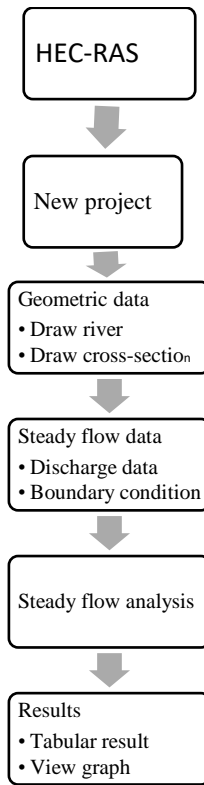


Fig. 3.4: Flow chart of HEC-RAS model

RESULTS AND DISCUSSION

In this section, methodologies adopted and their findings have been discussed for degerming the environmental flows for five selected fish species.

4.1 Identification of Keystone Species and their Habitat Requirement

4.1.1 Keystone species in Godavari river basin

The Godavari is one of the richest rivers with respect to fish diversity in peninsular India. More than 90 species of fish inhabit the downstream section of this river, and about 60 fish species have been reported from the proposed dam site at Polavaram, East Godavari District, Andhra Pradesh (Sivakumar et al., 2014). Among these, *B. dero*, *C. cirrhosus*, *L. calbasu* and *L. fimbriatus* were the most common economically important fishes (Sivakumar et al., 2014). These are also the most common species in other rivers and irrigation canals of peninsular India (Talwar and Jhingan, 1991; Jayaram and Dhas, 2000). They live in a broad range of flow conditions, and their abundance in the Godavari is due to the wide range of suitable habitat conditions available in this river. However, *W. attu*, which is also an economically important and large-sized fish, was less frequently encountered during the sampling period. This might be due to overexploitation of this species for food, as there is a great demand for it in the local market (Mishra et al., 2009; <http://www.iucnredlist.org>).

In Godavari river basin, total 60 species of native fish were recorded by Johnson et al. (2017) from the study area. The fish populations were dominated by Cyprinidae, which contribute about 35% of fish catch. Among the cyprinids, *B. dero*, *C. cirrhosus*, *L. calbasu* and *L. fimbriatus* were dominant in the fish catch. The catfish *W. attu* was relatively rare in the study area. Small cyprinids such as danio, barils, rasbora, barbs and loaches were found along the banks of the river channel as well as streams. The cyprinids were the dominant group, and these constituted 42% of the species assemblage structure.

On the basis of existing literature, five fish species viz. viz. *Bangana dero*, *Cirrhinus cirrhosis*, *Labeo calbasu*, *Labeo fimbriatus*, *Wallgo attu* have been considered as keystone fish species in the study area for the assessment of environmental flows.

4.1.2 Habitat requirement of keystone species

As evident from the literature, there are five keystone fish species in the study area viz. *Bangana dero*, *Cirrhinus cirrhosis*, *Labeo calbasu*, *Labeo fimbriatus*, *Wallgo attu*.

Johnson et al. (2017) carried out the fisheries survey and developed the habitat suitability curves for these five fish species (as shown in Fig. 4.1 to Fig. 4.5).

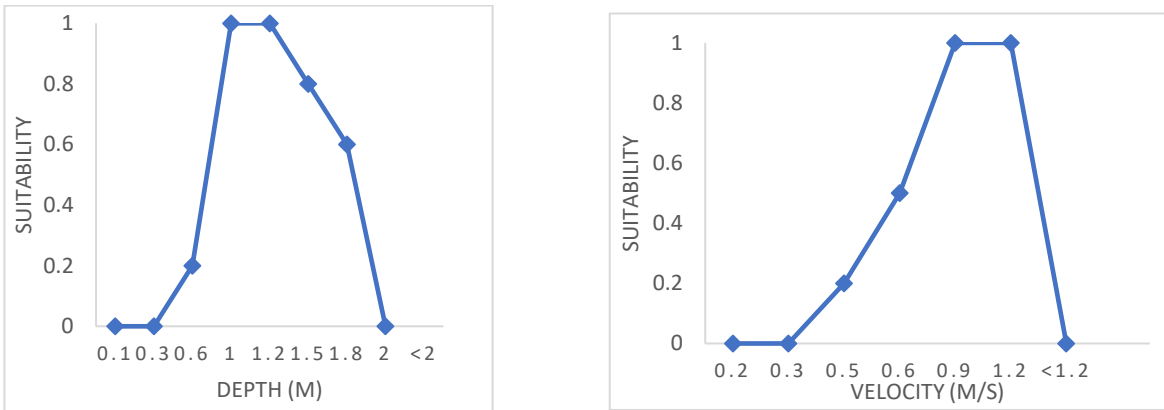


Fig. 4.1: Habitat suitability curves for bangana dero

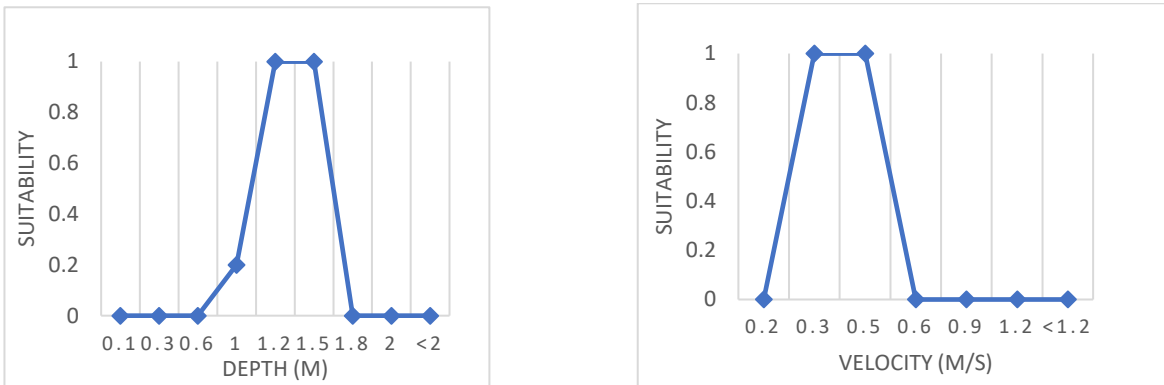


Fig. 4.2: Habitat suitability curve for cirrhinus cirrhosis

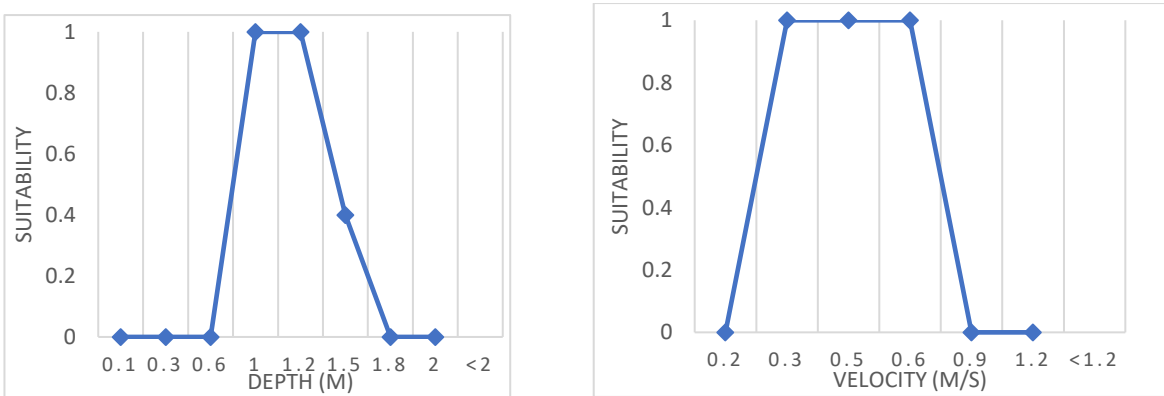


Fig. 4.3: Habitat suitability curves for labeo calbasu

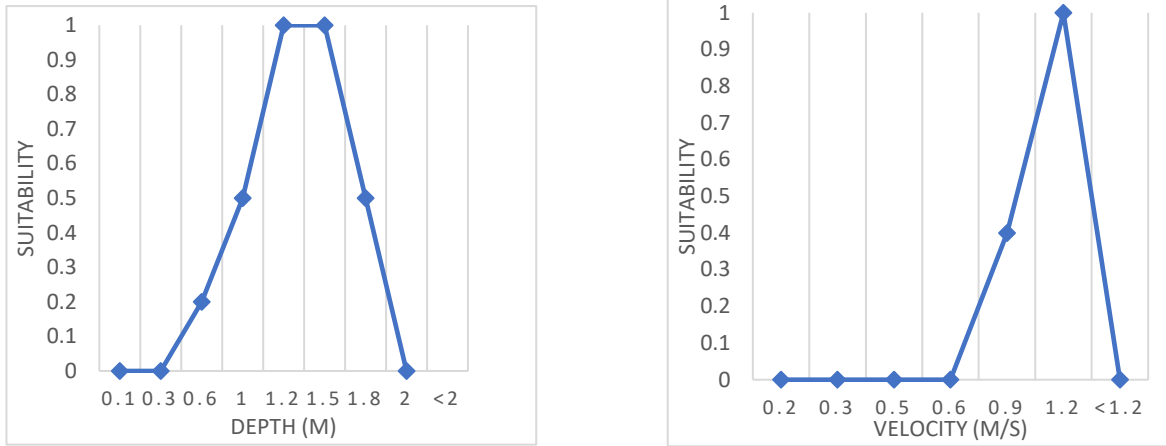


Fig. 4.4: Habitat suitability curves for laeob fimbriatus

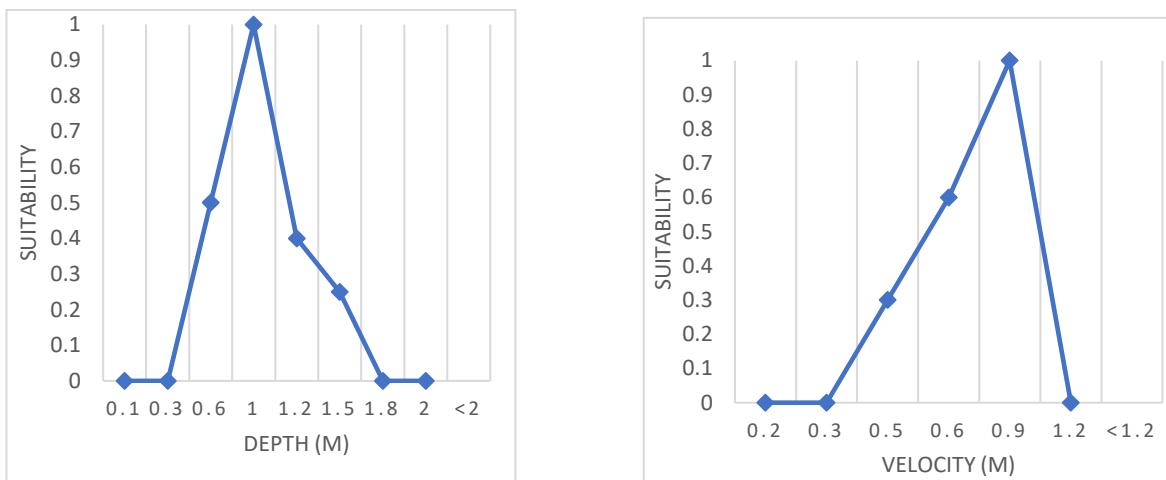


Fig. 4.5: Habitat suitability curves for wallago attu

4.2 Estimation of Relationship Between Discharge and Hydraulic Parameters

The relations between discharge and wetted perimeter, channel top width, channel depth, channel velocity at the selected location were estimated from the simulations through HEC-RAS model for the three seasons (monsoon, winter and summer) of dry, normal and wet years.

4.2.1 Identification of dry, normal and wet years

Probability analysis of the annual runoff at Satrapur site was carried out using the daily discharge data of Godavari river at Satrapur site. The daily discharge values were arranged from June to May and converted into annual runoff volumes. Further, Weibull's method was used for the probability analysis. The obtained values are given in Table 4.1. The year corresponding to the flows pertaining to desired probability i.e. Q90(dry year), Q50(normal year) and Q10(wet year) was read from table. From the table, it is seen that the dry, normal and wet years were 2004-2005, 2011-2012, 1999-2000 respectively.

4.2.2 Estimation of average flows during different season of dry, normal and wet years

The year has been divided into three different seasons based on the flow regime as follows:

Season I: It is considered as high flow season influenced by monsoon. It covers the months from June to September. These 4 months have been considered as monsoon months.

Season II: This season is considered as average flow period, covers the months from October to January. These months have been considered as non-monsoon non lean months.

Season III: This season is considered as low or lean or dry flow season which covers the months from February to May. These months have been considered as lean months.

The discharges data of Godavari river at Satrapur site was used to obtain the average flows during different seasons for the dry, normal and wet years. The summary of average flows during different seasons and during dry, normal and wet years are given in Table 4.2. It was observed that in the case of dry season (Q90) the discharge for monsoon, winter and summer seasons was 51.367, 7.101, 0.763 m³/s , respectively while for normal year (Q50) the discharge for monsoon, winter and summer was 144.475, 17.655 and 5.0171 m³/s, respectively and for wet year (Q10) the discharge for monsoon, winter and summer season was 342.795, 120.642 and 9.350 respectively.

Table 4.1: Probability analysis of annual runoff data

Year	Annual runoff	Probability	P*100	Identified year
1994-1995	6822.578938	0.032258065	3.225806452	
2013-2014	6740.391888	0.064516129	6.451612903	
1999-2000	4993.183267	0.096774194	9.677419355	Q10, Wet Year
1997-1998	3927.756528	0.129032258	12.90322581	
2012-2013	2988.295373	0.161290323	16.12903226	
1988-1989	2553.72791	0.193548387	19.35483871	
1993-1994	2401.881379	0.225806452	22.58064516	
2005-2006	2380.949338	0.258064516	25.80645161	
1990-1991	2290.496918	0.290322581	29.03225806	
1998-1999	2136.097699	0.322580645	32.25806452	
2003-2004	2060.757677	0.35483871	35.48387097	
2007-2008	1918.942704	0.387096774	38.70967742	
2006-2007	1880.668541	0.419354839	41.93548387	
2010-2011	1770.865027	0.451612903	45.16129032	
2011-2012	1762.95528	0.483870968	48.38709677	Q50, Normal Year

1992-1993	1548.261389	0.516129032	51.61290323	
2009-2010	1489.112208	0.548387097	54.83870968	
2016-2017	1458.012614	0.580645161	58.06451613	
1995-1996	1426.172659	0.612903226	61.29032258	
1991-1992	1405.945814	0.64516129	64.51612903	
2015-2016	1401.125299	0.677419355	67.74193548	
1996-1997	1183.919501	0.709677419	70.96774194	
2014-2015	1126.943194	0.741935484	74.19354839	
1989-1990	1040.583283	0.677419355	67.74193548	
2002-2003	889.6741056	0.806451613	80.64516129	
2000-2001	863.4976704	0.838709677	83.87096774	
2001-2002	782.7236928	0.870967742	87.09677419	
2004-2005	624.8375424	0.903225806	90.32258065	Q90, Dry year
1987-1988	413.2843776	0.935483871	93.5483871	
2008-2009	395.6262048	0.967741935	96.77419355	

Table 4.2: Seasonal average flows (cumecs) during dry, normal and wet years

Dry year (Q90)			Normal year (Q50)			Wet year (Q10)		
Monsoon	Winter	Summer	Monsoon	Winter	Summer	Monsoon	Winter	Summer
51.367	7.101	0.763	144.475	17.655	5.0171	342.795	120.642	9.350

4.2.3 HEC-RAS Model Set Up at Satrapur Site

Using the DEM file of the study area, HEC-RAS model has been set up and used for estimating the hydraulic parameters (depth of flow, flow velocity, flow area and top flow width) corresponding to different percentage releases of the average flows during the three seasons in Dry, Normal and Wet years. The HEC-RAS model set up at Satrapur site is shown in Fig. 4.6 and Fig. 4.7. The flows considered for estimating the hydraulic parameters are summarized in Table 4.3.

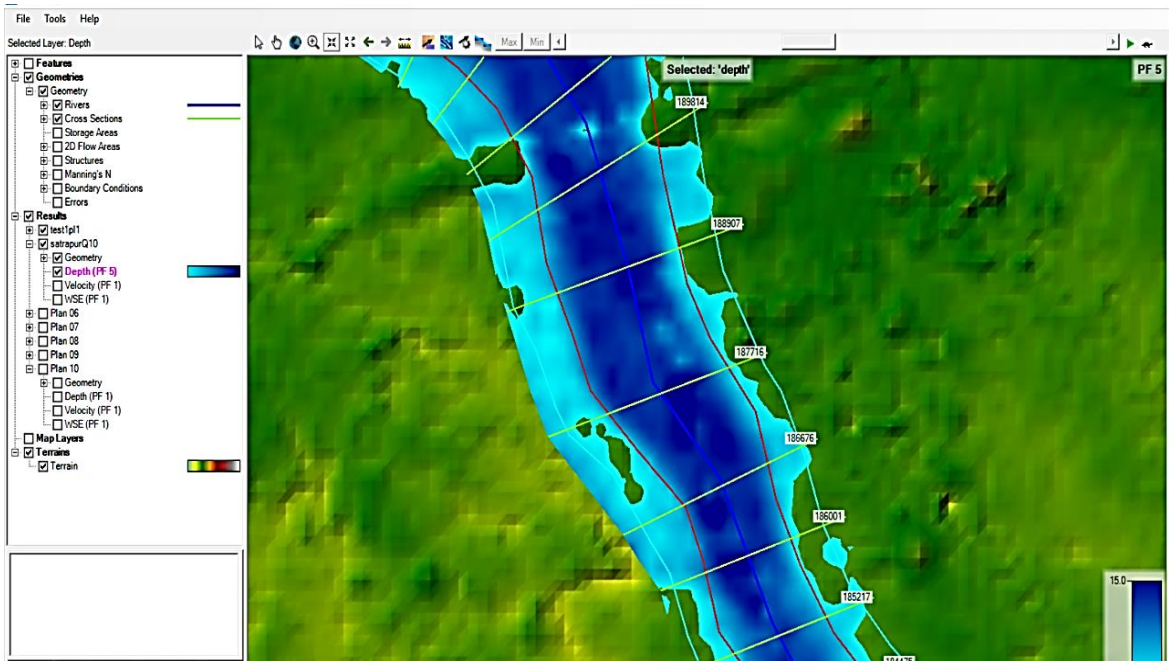


Fig. 4.6: HEC-RAS model set up at Satrapur for estimating the hydraulic parameters

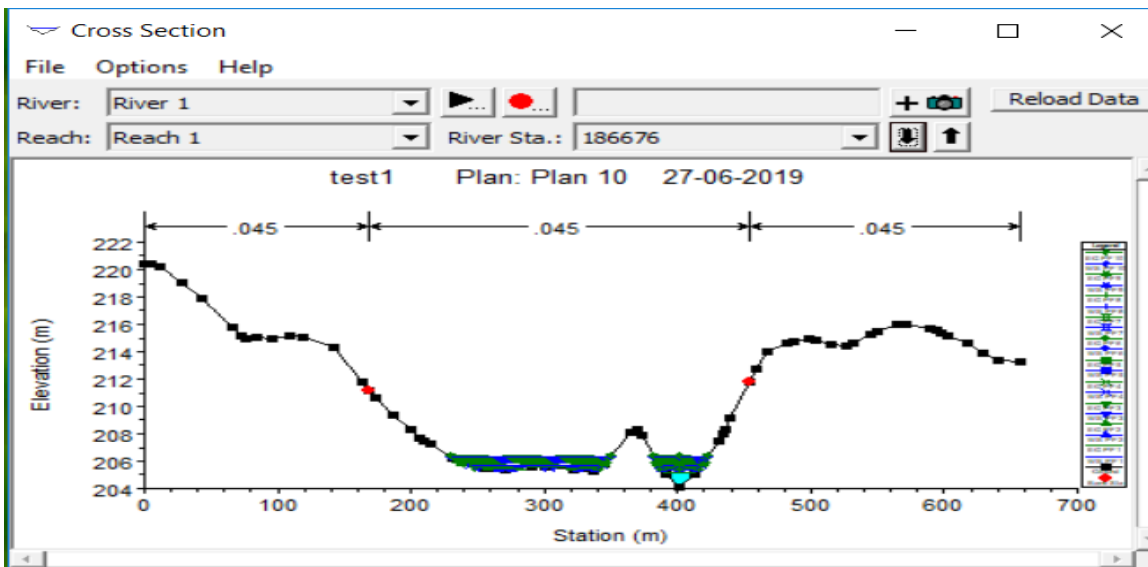


Fig. 4.7: Cross-section visualization in HEC-RAS at Satrapur site

4.2.4 Relationships between discharge and hydraulic parameters

The set-up HEC RAS model was used to estimate the hydraulic parameters at Satrapur site corresponding to the various percentages of average flows during monsoon, winter and summer seasons for the dry, normal and wet years. These flow values are given in Table 4.3.

Table 4.3: Various percentages of seasonal average flows during dry, normal and wet years

Season	Dry year (Q90)			Normal year (Q50)			Wet year (Q10)		
	Monsoon	Winter	Summer	Monsoon	Winter	Summer	Monsoon	Winter	Summer
0.1Q_{AV}	5.136	0.710	0.0763	14.447	1.765	0.501	34.2795	12.064	0.935
0.2Q_{AV}	10.273	1.420	0.152	28.894	3.531	1.003	68.559	24.128	1.870
0.3Q_{AV}	15.410	2.130	0.228	43.342	5.296	1.505	102.838	36.192	2.805
0.4Q_{AV}	20.547	2.840	0.305	57.789	7.062	2.006	137.118	48.256	3.740
0.5Q_{AV}	25.683	3.550	0.381	72.237	8.827	2.508	171.397	60.321	4.675
0.6Q_{AV}	30.820	4.261	0.457	86.684	10.593	3.011	205.677	72.385	5.610
0.7Q_{AV}	35.957	4.971	0.534	101.132	12.359	3.512	239.956	84.449	6.545
0.8Q_{AV}	41.094	5.681	0.610	115.58	14.124	4.0137	274.236	96.513	7.480
0.9Q_{AV}	46.230	6.391	0.686	130.027	15.89	4.515	308.515	108.578	8.415
1.0Q_{AV}	51.367	7.101	0.763	144.475	17.655	5.0171	342.795	120.642	9.350

HEC-RAS model was run for the different percentages of average flows during three seasons corresponding to dry, normal and wet years. The hydraulic parameters obtained through these simulations have been presented in Tables 4.4 to 4.12. For dry period, during monsoon season hydraulic depth, wetted perimeter, top width, velocity and flow area varies from 0.42 to 1.1 m, 81.01 to 80.69 m, 80.69 to 149.09 m, 0.246 to 0.43 m/sec and 154.52 to 245.52 m², respectively, during winter season hydraulic depth, wetted perimeter, top width, velocity and flow area varies from 0.35 to 0.46 m, 62.34667 to 84.9 m, 62.06 to 84.58667 m, 0.07 to 0.29333 m/sec and 134.64 to 160.5933 m², respectively and during summer season hydraulic depth, wetted perimeter, top width, velocity and flow area varies from 0.25 to 0.35 m, 58.0533 to 62.566 m, 57.78 to 62.28 m, 0.0133 to 0.6333 m/sec and 130.47 to 254.07 m², respectively, whereas for normal period, hydraulic depth, wetted perimeter, top width, velocity and flow area varies from 0.65 to 1.23 m, 90.3466 to 219.344 m, 90.1 to 218.9133 m, 0.43667 to 0.50667 m/sec and 205.89 to 388.3433 m², respectively, during monsoon season, hydraulic depth, wetted perimeter, top width, velocity and flow area varies from 0.36 to 0.71 m, 69.2233 to 94.83667 m, 68.93 to 94.4933 m, 0.13 to 0.46333 m/sec and 141.1333 to 185.1333 m², respectively, during winter season and hydraulic depth, wetted perimeter, top width, velocity and flow area varies from 0.33 to 0.42 m, 61.39 to 80.9667 m, 61.1033 to 80.39 m, 0.056667 to 0.24 m/sec and 132.8533 to 154.1433 m², respectively, during summer season. And for wet period, during monsoon season hydraulic depth, wetted perimeter, top width, velocity and flow area varies from 0.94 to 2.02 m,

129.6033 to 255.8367 m, 129.2167 to 255.17 m, 0.47667 to 0.67 m/sec and 215.4967 to 610.6633 m², respectively, during winter season hydraulic depth, wetted perimeter, top width, velocity and flow area varies from 0.59 to 1.09 m, 87.85 to 210.34 m, 87.51667 to 209.83 m, 0.38333 to 0.4833 m/sec and 173.2367 to 353.9433 m², respectively and during summer season hydraulic depth, wetted perimeter, top width, velocity and flow area varies from 0.37 to 0.53 m, 63.2166 to 86.3833 m, 62.9333 to 86.05667 m, 0.08667 to 0.33667 m/sec and 136.3 to 166.7133 m², respectively.

Table 4.4: Discharge and hydraulic parameters during monsoon season for dry year

Profile	Q total (m ³ /s)	Hydr. depth (m)	Wetted P (m)	Top width (m)	Velocity (m/s)	Flow area (m ²)
0.1Q90	5.14	0.42	81.01	80.69667	0.246667	154.5233
0.2Q90	10.27	0.55	86.92	86.59333	0.353333	169.0133
0.3Q90	15.41	0.67	91.40667	91.06667	0.43	180.5533
0.4Q90	20.55	0.76	98.97667	98.62333	0.486667	190.7567
0.5Q90	25.68	0.84	110.4933	110.13	0.51	200.1667
0.6Q90	30.82	0.9	122.96	122.5767	0.49	209.31
0.7Q90	35.96	0.95	135.2067	134.8167	0.463333	218.51
0.8Q90	41.09	1.01	142.1367	141.7367	0.443333	227.8567
0.9Q90	46.23	1.06	145.97	145.56	0.436667	236.8567
1.0Q90	51.37	1.1	149.51	149.0933	0.433333	245.5267

Table 4.5: Discharge and hydraulic parameters during winter season for dry year

Profile	Q total (m ³ /s)	Hydr. depth (m)	Wetted P (m)	Top width (m)	Velocity (m/s)	Flow area (m ²)
0.1Q90	0.71	0.35	62.34667	62.06	0.07	134.64
0.2Q90	1.42	0.36	67.34667	67.05667	0.113333	139.2733
0.3Q90	2.13	0.37	70.95333	70.65667	0.15	142.96
0.4Q90	2.84	0.38	73.85667	73.55667	0.176667	146.1233
0.5Q90	3.55	0.4	76.36333	76.06333	0.2	148.9733
0.6Q90	4.26	0.41	78.57	78.26	0.22	151.5633
0.7Q90	4.97	0.42	80.56667	80.25667	0.24	153.9833
0.8Q90	5.68	0.43	82.42667	82.11333	0.26	156.28
0.9Q90	6.39	0.44	84.16	83.84667	0.28	158.48

1.0Q90	7.1	0.46	84.9	84.58667	0.293333	160.5933
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Table 4.6: Discharge and hydraulic parameters during summer season for dry year

Profile	Q total (m ³ /s)	Hydr. depth (m)	Wetted P (m)	Top width (m)	Velocity (m/s)	Flow area (m ²)
0.1Q90	0.08	0.25	58.05333	57.78	0.013333	252.2067
0.2Q90	0.15	0.27	58.97667	58.69667	0.023333	254.07
0.3Q90	0.23	0.29	59.65667	59.38	0.03	193.115
0.4Q90	0.31	0.3	60.22667	59.94667	0.04	130.4767
0.5Q90	0.38	0.31	60.72	60.43667	0.046667	131.4167
0.6Q90	0.46	0.32	61.15333	60.87	0.05	132.24
0.7Q90	0.53	0.33	61.54333	61.26	0.06	132.9733
0.8Q90	0.61	0.34	61.91	61.62667	0.063333	133.6733
0.9Q90	0.69	0.35	62.26	61.97667	0.07	134.3367
1.0Q90	0.76	0.35	62.56667	62.28	0.076667	134.92

Table 4.7: Discharge and hydraulic parameters during monsoon season for normal year

Profile	Q total (m ³ /s)	Hydr. depth (m)	Wetted P (m)	Top width (m)	Velocity (m/s)	Flow area (m ²)
0.1Q50	14.45	0.65	90.34667	90.01	0.42	178.4967
0.2Q50	28.89	0.88	118.0867	117.71	0.5	205.89
0.3Q50	43.34	1.03	143.8767	143.4767	0.436667	231.8333
0.4Q50	57.79	1.16	153.7633	153.34	0.436667	256.0567
0.5Q50	72.24	1.19	164.19	163.7433	0.446667	278.63
0.6Q50	86.68	0.97	187.63	187.16	0.463333	300.9667
0.7Q50	101.13	0.99	199.4467	198.96	0.47	323.7967
0.8Q50	115.58	1.05	208.2267	207.7233	0.483333	346.2
0.9Q50	130.03	1.15	214.0833	213.5667	0.493333	367.8667
1.0Q50	144.47	1.23	219.4433	218.9133	0.506667	388.6433

Table 4.8: Discharge and hydraulic parameters during winter season for normal year

Profile	Q total (m³/s)	Hydr. depth (m)	Wetted P (m)	Top width (m)	Velocity (m/s)	Flow area (m²)
0.1Q50	1.77	0.36	69.22333	68.93	0.13	141.1333
0.2Q50	3.53	0.4	76.28	75.97667	0.2	148.8767
0.3Q50	5.3	0.43	81.43667	81.12333	0.25	155.05
0.4Q50	7.06	0.46	84.87333	84.55667	0.293333	160.4733
0.5Q50	8.83	0.51	86.05333	85.73	0.326667	165.3433
0.6Q50	10.59	0.56	87.09333	86.76333	0.356667	169.7967
0.7Q50	12.36	0.6	87.99667	87.66333	0.386667	173.9033
0.8Q50	14.12	0.64	89.99333	89.65667	0.416667	177.8133
0.9Q50	15.89	0.68	92.12667	91.78333	0.443333	181.5467
1.0Q50	17.66	0.71	94.83667	94.49333	0.463333	185.1333

Table 4.9: Discharge and hydraulic parameter during summer season for normal year

Profile	Q total (m³/s)	Hydr. depth (m)	Wetted P (m)	Top width (m)	Velocity (m/s)	Flow area (m²)
0.1Q50	0.5	0.33	61.39	61.10333	0.056667	132.8533
0.2Q50	1	0.37	63.45667	63.16667	0.09	136.7567
0.3Q50	1.51	0.36	67.89	67.59667	0.12	139.7533
0.4Q50	2.01	0.37	70.40333	70.10667	0.146667	142.3733
0.5Q50	2.51	0.38	72.56	72.26333	0.166667	144.6933
0.6Q50	3.01	0.39	74.48333	74.18333	0.183333	146.8233
0.7Q50	3.51	0.4	76.21333	75.91	0.2	148.7967
0.8Q50	4.01	0.41	77.81	77.50333	0.213333	150.6667
0.9Q50	4.52	0.41	79.30333	78.99333	0.23	152.4433
1.0Q50	5.02	0.42	80.69667	80.39	0.24	154.1433

Table 4.10: Discharge and hydraulic parameter during monsoon season for wet year

Profile	Q total (m³/s)	Hydr. depth (m)	Wetted P (m)	Top width (m)	Velocity (m/s)	Flow area (m²)
0.1Q10	34.28	0.94	129.6033	129.2167	0.476667	215.4967
0.2Q10	68.56	1.22	160.2867	159.84	0.443333	272.9533

0.3Q10	102.84	0.99	200.5867	200.0967	0.47	326.4567
0.4Q10	137.12	1.19	216.7967	216.2733	0.5	378.29
0.5Q10	171.4	1.38	228.49	227.93	0.53	424.9567
0.6Q10	205.68	1.54	238.7133	238.1267	0.56	467.7733
0.7Q10	239.96	1.68	244.0133	243.4067	0.59	507.72
0.8Q10	274.24	1.81	248.3333	247.7033	0.613333	545.5167
0.9Q10	308.52	1.93	252.4733	251.8233	0.64	581.4067
1.0Q10	342.8	2.02	255.8367	255.17	0.67	610.6633

Table 4.11: Discharge and hydraulic parameter during winter season for wet year

Profile	Q total (m ³ /s)	Hydr. depth (m)	Wetted P (m)	Top width (m)	Velocity (m/s)	Flow area (m ²)
0.1Q10	12.06	0.59	87.85	87.51667	0.383333	173.2367
0.2Q10	24.13	0.81	106.89	106.5267	0.506667	197.3767
0.3Q10	36.19	0.96	135.6467	135.26	0.46	218.9567
0.4Q10	48.26	1.07	147.4033	146.99	0.433333	240.3333
0.5Q10	60.32	1.17	155.3867	154.9567	0.436667	260.13
0.6Q10	72.39	1.19	164.3233	163.8767	0.446667	278.83
0.7Q10	84.45	1.06	179.8367	179.3767	0.456667	297.4
0.8Q10	96.51	0.98	196.3333	195.8567	0.47	316.5967
0.9Q10	108.58	1.01	204.73	204.2333	0.48	335.4567
1.0Q10	120.64	1.09	210.34	209.83	0.483333	353.9433

Table 4.12: Discharge and hydraulic parameter during summer season for wet year

Profile	Q total (m ³ /s)	Hydr. depth (m)	Wetted P (m)	Top width (m)	Velocity (m/s)	Flow area (m ²)
0.1Q10	0.94	0.37	63.21667	62.93333	0.086667	136.3
0.2Q10	1.87	0.37	69.74667	69.45	0.136667	141.68
0.3Q10	2.81	0.38	73.72333	73.42	0.173333	145.9733
0.4Q10	3.74	0.4	76.98667	76.68	0.206667	149.7
0.5Q10	4.68	0.42	79.75	79.43667	0.233333	152.9833
0.6Q10	5.61	0.43	82.24	81.93333	0.256667	156.0567

0.7Q10	6.55	0.45	84.49667	84.18	0.283333	158.9667
0.8Q10	7.48	0.47	85.17	84.85	0.303333	161.6833
0.9Q10	8.42	0.5	85.79333	85.47	0.32	164.2633
1.0Q10	9.35	0.53	86.38333	86.05667	0.336667	166.7133

4.3 Assessment of Environmental Flows for Keystone Species

The environmental flows for Godavari river at the selected Satarpur site were assessed by using the habitat suitability curves for five keystone species and simulated values of depth corresponding to various discharge profiles generated considering the percentages of average flows during monsoon, winter and summer seasons for dry, normal and wet years. The relationship obtained from the simulated values of hydraulic depth corresponding to various discharges is shown in Fig. 4.8. The minimum depth requirement for best suitability of keystone species has been considered to assess the values of environmental flows as summarized in Table 4.13. Since, the values of environmental flows obtained are in the range of 14.16 cumecs to 102.21 cumecs. Assuming that the fulfilling the flow requirement of the keystone species requiring highest flows will also cover the flow requirement of other keystone species, it is found out that the minimum ecological flow requirement at Satarpur site in Godavari basin will be 102.21 cumec

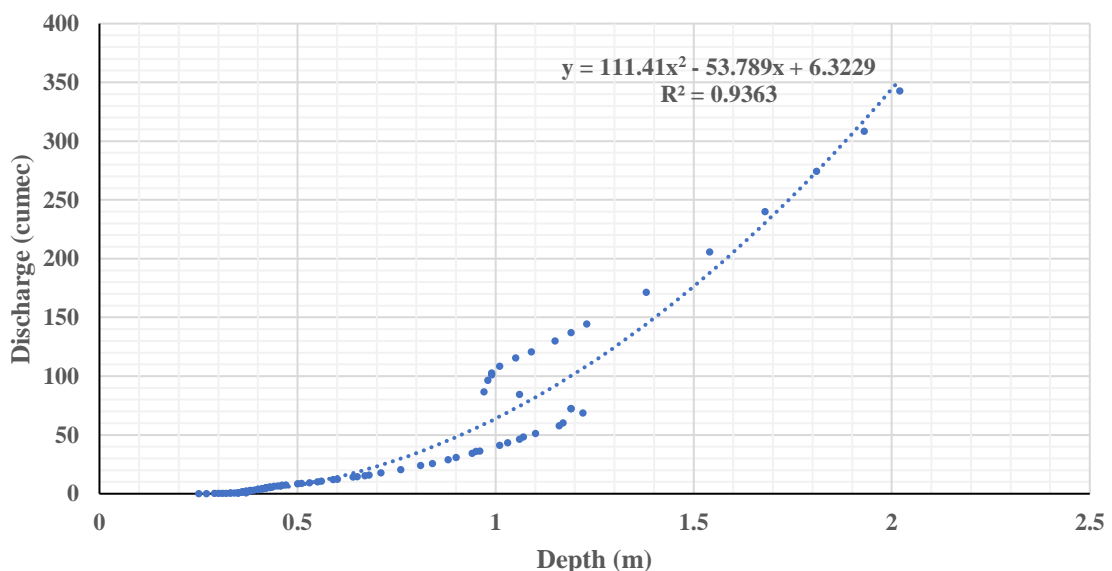


Fig. 4.8: Depth vs discharge relationship for Godavari river at Satrapur site

Table 4.13: Estimated environmental flows for keystone fish species in Godavari river at Satrapur site

Keystone species	Optimal Depth Requirement (m)	Optimal Discharge Requirement (m³/s)
Bangana dero	0.6	14.16
Cirrhinus cirrhosis	1.2	102.21
Labelo calbasu	1.0	63.94
Labelo fimbriatus	1.2	102.21
Wallago attu	1.0	63.94

On the basis of desired depth for all the five species corresponding discharge for sustaining the all fish species was estimated by HEC-RAS software. Two species namely Cirrhinus cirrhosis and Labelo fimbriatus requires 1.2 m depth for their survival and all other three species require depth less than that of both species, that's why discharge corresponding to 1.2 m depth has the most important role to sustain the river ecology and called as the environmental flow of Wainganga river Godavari basin at Satrapur gauging site.

SUMMARY AND CONCLUSIONS

5.1 Identification of Keystone Species and their Habitat Requirement

On the basis of existing literature, five fish species viz. *Bangana dero*, *Cirrhinus cirrhosis*, *Labeo calbasu*, *Labeo fimbriatus*, *Wallgo attu* have been considered as keystone fish species in the study area for the assessment of environmental flows. Johnson et al. (2017) carried out the fisheries survey and developed the habitat suitability curves for these five fish species which have been taken for further analysis in the study.

5.2 Estimation of Relationship Between Discharge and Hydraulic Parameters

The relations between discharge and wetted perimeter, channel top width, channel depth, channel velocity at the selected location were estimated from the simulations through HEC-RAS model for the three seasons (monsoon, winter and summer) of dry, normal and wet years. Probability analysis of the annual runoff at Satarpur site was carried out using the daily discharge data of Godavari river at Satarpur site. The daily discharge values were arranged from June to May and converted into annual runoff volumes.

The year has been divided into three different seasons based on the flow regime as follows:

Season I: It is considered as high flow season influenced by monsoon. It covers the months from June to September. These 4 months have been considered as monsoon months.

Season II: This season is considered as average flow period, covers the months from October to January. These months have been considered as non-monsoon non lean months.

Season III: This season is considered as low or lean or dry flow season which covers the months from February to May. These months have been considered as lean months.

Using the DEM file of the study area, HEC-RAS model has been set up and used for estimating the hydraulic parameters (depth of flow, flow velocity, flow area and top flow width) corresponding to different percentage releases of the average flows during the three seasons in Dry, Normal and Wet years. The set-up HEC RAS model was used to estimate the hydraulic parameters at Satarpur site corresponding to the various percentages of average flows during monsoon, winter and summer seasons for the dry, normal and wet years. HEC-RAS model was run for the different percentages of average flows during three seasons corresponding to dry, normal and wet years.

5.3 Assessment of Environmental Flows for Keystone Species

The environmental flows for Godavari river at the selected Satarpur site were assessed by using the habitat suitability curves for five keystone species and simulated values of depth corresponding to various discharge profiles generated considering the percentages of average flows during monsoon, winter and summer seasons for dry, normal and wet years. Following conclusion has been drawn;

- Five keystone fish species namely *Bangana dero*, *Cirrhinus cirrhosis*, *Labeo calbasu*, *Labeo fimbriatus* and *Wallgo attu* found in the river were selected and desired depth of each species was taken from existing literature (Johnson *et al.*, 2017).
- The desired depths for *Bangana dero*, *Cirrhinus cirrhosis*, *Labeo calbasu*, *Labeo fimbriatus* and *Wallgo attu* were found 0.6, 1.2, 1.0, 1.2, 1.0 m and corresponding discharge were found 14.16, 102.21, 63.94, 102.21, 63.94 m³/s, respectively.
- From the probability analysis, it was concluded that the year 2004-2005, 2011-2012, 1999-2000 are classified as dry (with 624.83 m³/sec discharge for 90 % of the time), normal (with 1762.95m³/sec discharge for 50 % of the time) and wet (with 4993.183267 m³/sec discharge for 10 % of the time) year.
- On the basis of probability analysis discharge for dry year with Q90 during monsoon, winter and summer seasons was found 51.367, 7.101, 0.763 m³/s , respectively while for normal year (Q50) the discharge for monsoon, winter and summer was 144.475, 17.655 and 5.0171 m³/s, respectively and for wet year (Q10) the discharge for monsoon, winter and summer season was 342.795, 120.642 and 9.350 respectively
- Discharge (102.21 m³/s) corresponding 1.2 m depth was found as environmental flows of Wainganga river Godavari basin at Satrapur gauging site.

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