Final Report

Development of Habitat Suitability Curves for the Aquatic Species of Western Himalayan Streams and Assessment of Environmental Flows

NATIONAL INSTITUTE OF HYDROLOGY
(An ISO 9001:2008 Institute under MoWR, RD & GR, Govt of India)
ROORKEE – 247 667 (UTTARAKHAND)

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER - 1
INTRODUCTION

1.1 BACKGROUND

The rivers are increasingly being modified through impoundments such as dams and weirs, abstractions for hydropower generation, agriculture and urban water supply, drainage return flows, maintenance of flows for navigation, and structures for flood control. 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. This has led to widespread degradation of aquatic ecosystems.

Right from the place of its origin to its outfall in the sea (or a bigger river), a naturally flowing fresh water river provides the habitat for a variety of diverse life forms. In many developing countries, a river also meets the needs of people on its banks. The livelihoods of many fisher folk, boatmen and farmers are supported by the river. Hundreds of religious and cultural events are organized regularly on river banks. All these benefits are provided by naturally flowing rivers without any costs being incurred, and these benefits are for all times. When the flow of rivers is reduced by storage and diversion and joined by water from polluted streams, many of these benefits are sacrificed.

Variability and seasonality of flows in tropical countries such as India is characterised by a high percentage of annual rainfall (70 % to 85 %) occurring in monsoon season (June/July to September/October)**.** Tropical monsoon hydrology necessitates development of storage and flow diversion schemes on rainfed and perennial rivers for multipurpose utilization of water particularly for hydropower generation and irrigation for which high demand exists throughout the year. Himalayan rivers being snowfed are characterised by perennial flows and steep gradients offering abundant scope for hydropower development. A large number of hydropower schemes in the Himalayan mountainous region spread over parts of India, Nepal, Bhutan and Pakistan are in different stages of development.

A hydropower project usually consists of a control structure on the river (dam with or without significant storage), a water conveyance system (tunnel, canal) and a power house. The power house is located at a distance in downstream where topographical head difference between dam location and power house location is utilised for power generation and water is returned to the river (Fig. 1.1). In several cases, water conveyance system and power house are located underground. A river reach is deprived of its natural flows due to diversion at control structure. Further, flow in the tributaries within a river reach may get modified due to various construction activities and also if tributary flows are diverted into the conveyance system. Thus, the natural flow regime is altered not only in a river reach downstream of control structure but at several places within a catchment associated with the project layout.

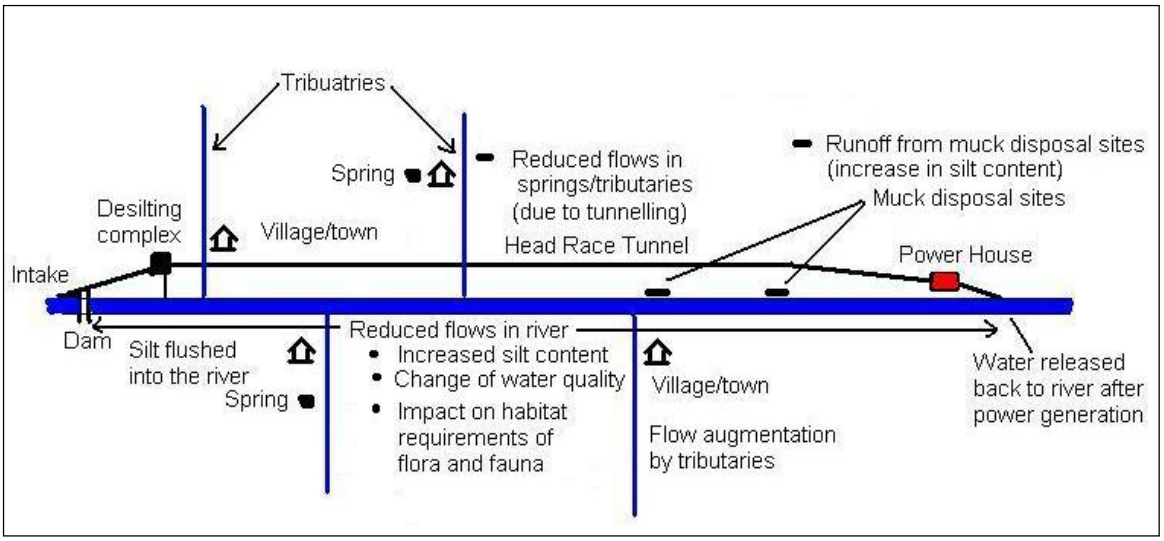


Fig. 1.1: Layout of a hydropower project and flow related impacts

There may be critical reaches in the river where altered flows are not able to sustain the ecosystem services existing prior to implementation of the hydropower scheme. The developmental planning process in eco-sensitive and fragile Himalayan mountainous region should ensure that the biodiversity and ecological integrity of the aquatic and terrestrial ecosystems are protected and conserved.

1.2 ENVIRONMENTAL FLOW

An environmental flow is the water regime provided within a river to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated. Environmental flows provide critical contributions to river health, economic development and poverty alleviation. They ensure the continued availability of the many benefits that healthy river and groundwater systems bring to society.

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 variety of purposes including religious worship.

For day-to-day management of particular rivers, environmental requirements are often defined as a suite of flow discharges of certain magnitude, timing, frequency and duration. These flows ensure a flow regime capable of sustaining a complex set of aquatic habitats and ecosystem processes and are referred to as “environmental flows”, “environmental water requirements”, “environmental flow requirements”, “environmental water demand” etc.. Many methods for determining these requirements have emerged in recent years. They are known as environmental flow assessments (EFA).

1.3 PROBLEM DEFINITION

Western Himalayan region is the main stay of the Himalayan water tower holding more than 90% of glacier and cryospheric resources in India and abundant monsoon rainfall along its foothills. Major rivers of the region; Ganga, Yamuna, Sutlej, Beas, Chenab, Jhelum, Zanskar, Indus, Shyok and Nubra all originate from the mighty Himalayas and contribute immensely to the development of our country and our neighbouring countries.

All the rivers of this region have huge hydropower potential. A number of hydropower schemes on these rivers are in different stages of planning, construction and operation. In most of these schemes, river water is diverted for power generation and returned to the river at a downstream location depriving the river of its natural flow in specific reaches. Even if the individual schemes may not be significantly detrimental the physical and biotic environment, the combined effect of these schemes could be significant. The problem may be more complex as the climate change and the land use changes are also affecting the hydrologic regime of these rivers.

A number of attempts for assessing E-Flows in this region have been made during last 15 years (Jain and Kumar, 2014). But, these efforts have been mostly based on hydrological or hydraulic approaches with application of limited habitat preferences. These studies are limited by the fact that neither the data on abundance of aquatic species is available nor there is any developed hydrology-ecology relationships. In this connection, the present study is envisaged to develop habitat suitability curves for the aquatic species of western Himalayan streams and to use these curves for the assessment of environmental flows using hbitat simulation modelling.

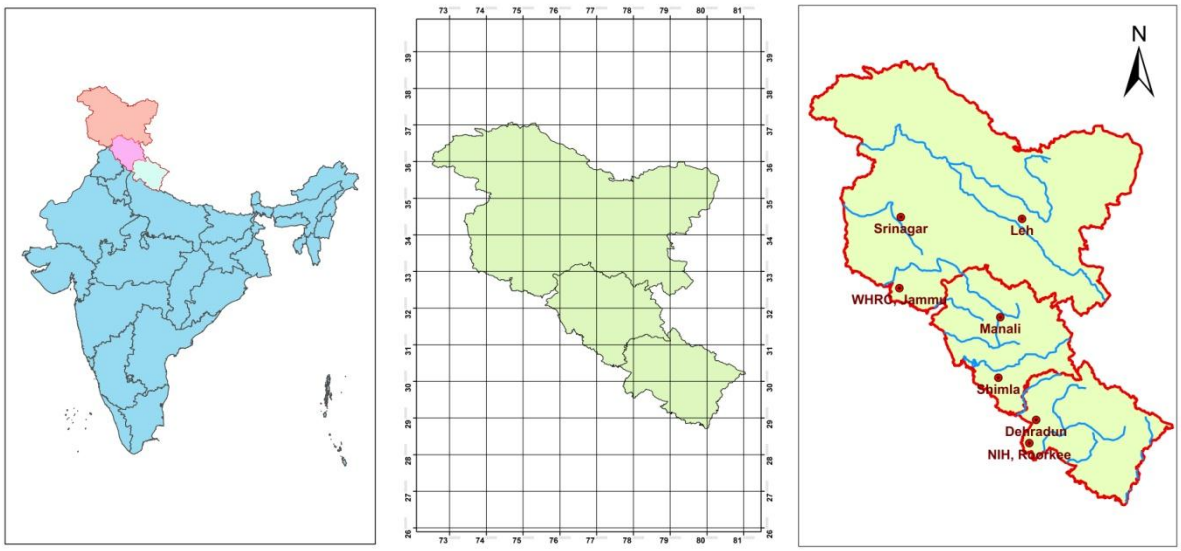
1.4 OBJECTIVES

The broad objectives for this study are as follows:

a. To compile the data/information on biotic parameters (abundance of aquatic species) and influencing abiotic parameters (water depth & velocity and water quality parameters: water temperature, pH, DO, BOD, turbidity etc.)
b. To identify the significant relationships between biotic and abiotic parameter and among the biotic parameters at selected locations
c. To establish the habitat suitability curves for keystone aquatic species
d. Assessment of environmental flows at selected sites using the developed habitat suitability curves.

CHAPTER – 2
STUDY AREA

Western Himalayan Region encompasses the major part of the Himalayan water tower. Two major river systems of the sub-continent, the Indus and the Ganges, which flow through some of the most populous regions on the earth, constitute the main surface drainage system of this region. This region is discernible with its mountainous terrain which has influence on the climate of the sub-continent. The region has abundant water resources in the form of glaciers, snow, springs, lakes and groundwater and has diverse hydrological regimes dominated by monsoon rainfall, winter snow as well as the cold-arid regions of Ladakh. Water resources issues of the region are also wide-ranging that demonstrates the various hydrological regimes of the area. Projected climate change impact on the mountain eco-systems has added another dimension to water resource planning and management in the region, and sound understanding of water resources systems of this region through systematic research is need of the hour. The location map of western Himalayan region has been shown in Fig. 2.1.



(a) Location in India (b) Geographic location (c) Major cities and rivers

Fig. 2.1: Western Himalayan Region

2.1 WATER RESOURCES DEVELOPMENT IN WESTERN HIMALAYAN REGION

Due to abundant water resources and steep gradient, a large number of water resources projects particularly hydropower projects on the Himalayan rivers are in different stages of development. These river valley schemes will cause flow related impacts due to storage, flow diversion, tunnelling, muck disposal etc. 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 storage and diversion schemes. The summary of hydropower projects in the western Himalayan region has been given in Table 2.1.

Table 2.1: Sub-basin wise number and type of water resources structures in the western Himalayan region

S. No.	Name of Sub-basin	Dam	Barrage	Weir	Lift	Power house
Ganga Basin						
1.	Ganga Sub-Basin above Ramganga Confluence	3	9	0	0	11
2.	Kosi	0	0	2	0	1
3.	Ramganga	11	9	1	0	1
4.	Tons	32	3	1	2	2
5.	Yamuna Upper	6	9	3	6	14
Indus Basin						
1.	Beas Sub Basin	11	2	5	4	16
2.	Upper Indus Sub Basin	1	2	3	0	4
3.	Satluj Upper Sub Basin	4	1	2	0	10
4.	Satluj Lower Sub Basin	7	4	0	3	6
5.	Shyok Sub Basin	0	0	0	0	0
6.	Ravi Sub Basin	7	3	1	2	9
7.	Lower Indus Sub Basin	0	0	0	0	0
8.	Jhelum Sub Basin	3	1	5	26	8
9.	Gilgit Sub Basin	0	0	0	0	0
10.	Ghaghar and others Sub Basin	2	0	0	5	0
11.	Chenab Sub Basin	4	0	2	5	6

(Source: India-WRIS)

2.2 FLOW RELATED ADVERSE IMPACTS OF WATER RESOURCES PROJECTS

Right from the place of its origin to its outfall in the sea (or a bigger river), a naturally flowing fresh water river provides the habitat for a variety of diverse life forms. A river also meets the needs of the people living near its banks. The livelihoods of many fisher folk, boatmen and farmers are supported by the river. Hundreds of religious and cultural events are organized regularly on river banks. All these benefits are provided by naturally flowing rivers without incurring any significant cost, and these benefits are for all times.

The services provided by the naturally flowing freshwater river may be classified into two categories:

1. **Natural (For the river itself):** The services/functions provided by the river which are necessary for its own survival (river-aquifer interaction, transportation of solids/sediments/nutrients, habitat for variety of species)
2. **Anthropogenic (For the society):** The services/functions provided by the river which have evolved over time for fulfilling the needs of the society (livelihood of riparian

population, religious/cultural activities etc.). This category of services has been expanded through modifying the river continuity and flow regime (spatial and temporal variability of flow).

The water, food and energy demands are the basic requirements of the society. These demands are increasing day-by-day either due to increase in population or due to lifestyle changes (requiring more per capita demand of water, food and energy). Moreover, variability and seasonality of flows in Indian Rivers are characterized as tropical monsoon hydrology where very high percentage of annual rainfall and thus the flow (70% to 85%) occurs in monsoon season (June/July to September/October). This necessitates development of storage and flow diversion schemes on rivers for multipurpose utilization of water particularly for hydropower generation and irrigation for which high demand exists throughout the year. To fulfil these ever-increasing demands of water, food and energy in the tropical monsoon hydrologic conditions in India, a number of water resource projects (domestic water supply schemes, irrigation projects, hydropower projects or multi-purpose projects – combining at least two of these three categories) have come up which require storage or diversion of river water. There may be critical reaches in the river where altered flows are not able to sustain the ecosystem services existing prior to implementation of these types of projects.

2.2.1 Impacts of Storage Type Water Resource Projects

Fragmentation of river ecosystems

A dam acts as a barrier between the upstream and downstream movement of migratory river animals, such as salmon and trout. Some communities have also begun the practice of transporting migratory fish upstream to spawn via a barge.

Reservoir sedimentation

Rivers carry sediment down their riverbeds, allowing for the formation of depositional features such as river deltas, alluvial fans, braided rivers, oxbow lakes, levees and coastal shores. The construction of a dam blocks the flow of sediment downstream, leading to downstream erosion of these Sedimentary depositional environments, and increased sediment build-up in the reservoir. While the rate of sedimentation varies for each dam and each river, eventually all reservoirs develop a reduced water-storage capacity due to the exchange of storage space for sediment. Diminished storage capacity results in decreased ability to produce hydroelectric power, reduced availability of water for irrigation, and if left unaddressed, may ultimately result in the expiration of the dam and river.

Riverline and coastal erosion

As all dams result in reduced sediment load downstream, a dammed river is said to be "hungry" for sediment. Because the rate of deposition of sediment is greatly reduced since there is less to deposit but the rate of erosion remains nearly constant, the water flow erodes the river

shores and riverbed, threatening shoreline ecosystems, deepening the riverbed, and narrowing the river over time. This leads to a compromised water table, reduced water levels, homogenization of the river flow and thus reduced ecosystem variability, reduced support for wildlife, and reduced amount of sediment reaching coastal plains and deltas. This prompts coastal erosion, as beaches are unable to replenish what waves erode without the sediment deposition of supporting river systems. Downsteam channel erosion of dammed rivers is related to the morphology of the riverbed, which is different from directly studying the amounts of sedimentation because it is subject to specific long term conditions for each river system.

Effects on flood-dependent ecology and agriculture

In many developing countries the forest ecology of the floodplains depend on seasonal flooding from rivers. Also, flood recession cropping is practiced extensively whereby the land is cultivated taking advantage of the residual soil moisture after floods recede. Dams attenuate floods which may affect the ecology and agriculture.

2.2.2 Impacts of Run-of-the-River (Diversion Type) Water Resource Projects

Any storage or flow diversion scheme usually consists of a control structure on the river (either dam with/without significant storage or barrage), a water conveyance system (tunnel, canal). In case of hydropower projects, the diverted water joins the river within < 1km to 30km (depending upon the river flow and capacity of the hydropower project). Whereas, in case of irrigation projects, the diverted water does not meet directly with the source river and may come as return flow after travelling the long route of sub-surface flow.

In case of hydropower projects, the river reach from dam to the point where diverted water again meets the river is deprived of its natural flows due to diversion at control structure. Whereas, in case of irrigation projects, whole river downstream of the dam/barrage is deprived of the natural flows. The altered flow regime may have the following impacts:

Increased competition for various water uses

Consumptive Uses :

1. Human water demand
2. Animal water demand
3. Water quality maintenance
4. Silt flushing

Non-Consumptive Uses :

1. Habitat requirement of aquatic species

Disturbance of habitat for aquatic species

- Altered flow regime (altered hydraulic parameters : depth, velocity, wetted perimeter)
- Altered water quality (DO, BOD, pH, TDS, Coliform etc.)
- Disconnectivity for migratory species
- Disturbance of food chain of aquatic biota
- Self-purification capacity of river is destroyed

Increased concentration of pollutants

The pollutant concentration may be increased due to reduction in flows with same/increased pollutants). The pollutants may be :

- Sediment (due to desilting, soil erosion from from quarrying and muck disposal sites)
- Wastewater
  - domestic
  - industrial

CHAPTER – 3
METHODOLOGY

Several methods/methodologies have been proposed in the literature for assessment of environmental flows. These methods range from simplistic use of the hydrological record to establish minimum and flushing flows to sophisticated procedures linking changes in river discharge with 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. The evolution, development and application of these E-Flow methods have been discussed in this chapter.

3.1 EVOLUTION OF SCIENCE OF ENVIRONMENTAL FLOWS

The development of environmental flows assessment (EFA) methodologies began in 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).

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.

EFA methodologies have been classified in several ways by different organizations as shown in Table 3.1. 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 other reference) flow regime. Thus, top-down approaches are less susceptible to 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, Hatfield et al. 2013, Linnansaari et al., 2013).

The following groups of EFA methods/ methodologies have been reviewed in this chapter covering their origin and development.

3.2 OVERVIEW OF VARIOUS E-FLOW ASSESSMENT METHODOLOGIES

3.2.1 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 rely primarily on historical flow records. 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 equalled 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, rate of flood rise/fall etc).

Hydrological Index Methods provide a relatively rapid, non-resource intensive, but low resolution estimate of environmental flows. Therefore the methods are most appropriate at the planning level of water resources development, or in low controversy situations where they may be used as preliminary estimates.

Table 3.1: Categorization of EFA methodologies

Organization	Category	Sub-category	Example
IUCN (Dyson et al. 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		Tennant Method, Desktop method
	Hydraulic rating Method		Wetted Perimeter Method
	Habitat Simulation Methodologies		Instream Flow Incremental Methodology (IFIM), System for Environmental Flow Assessment (SEFA)
	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)

3.2.2 Hydrological 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) Range of Variability Approach (RVA):

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 modelled 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 25^{th} and 75^{th} 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 alongwith 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 (FREND, 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 equalled 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 hydrometeorologically 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 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, a 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.

(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. (2013) 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 Section 1.7.8. As the implementation of ELOHA may be resource intensive and time consuming, Ritcher et al. (2011), as an interim measure, proposed another method called 'Presumtive 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 is 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 analysed. Moving averages of preceding flow have shown 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 programmes so is compatible with the European Water Framework Directive.

3.2.3 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 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. 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 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 fulfil 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 bankful 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.

3.2.4 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. Environmental flow is predicted from habitat-discharge curves or habitat time and exceedence 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, modelled 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 modelled 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 exceedence 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 meso-scale 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 River 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.

3.2.5 Holistic Methodologies

Holistic Methodologies are actually frameworks that incorporate hydrological, hydraulic and habitat simulation models. They are the only EFA methodologies that explicitly

adopt a holistic, ecosystem based approach to environmental flow determination. A wide range of holistic methodologies has been developed and applied, in Australia, South Africa and United Kingdom.

Ecosystem components that are commonly considered in holistic assessments include geomorphology, hydraulic habitat, water quality, riparian and aquatic vegetation, macroinvertebrates, fish and other vertebrates with some dependency upon the river/riparian ecosystem (i.e. amphibians, reptiles, birds, mammals). Each of these components can be evaluated using a range of field and desktop techniques (Tharme, 1996; Arthington and Zalucki, 1998; Tharme, 2003) and their flow requirements are then incorporated into EFA recommendations. The popular holistic methodologies using various systematic approaches are discussed in more detail below.

3.2.5.1 Instream flow incremental methodology (IFIM)

The Instream Flow Incremental Methodology (IFIM) is a framework for addressing the impacts on river ecosystems of changing a river flow regime. The US Fish and Wildlife Service developed IFIM (Bovee, 1986; Bovee et al., 1998). In some states of the USA, the use of IFIM has become a legal requirement for assessing the impacts of dams or abstractions.

Advantages of IFIM include it being a comprehensive framework for considering both policy and technical issues and its problem-orientated structure. Its implicit quantitative nature integrating micro and macro-habitat is generally considered an advantage. Furthermore, its scenario-based approach is favoured for negotiations between water users, but may be less suitable in setting flow regimes to comply with ecological objectives.

Disadvantages of IFIM partly arise from its comprehensive nature. A full study takes a considerable time and because of the wide range of issues included, provides numerous avenues for criticism. Furthermore, it is important to understand the limitations of the models used, what they include, omit or simplify, and any further issues arising from the linkages of models. Quantification of uncertainty is an element that has been frequently overlooked. Many "IFIM" studies have been criticised, but these criticisms have often arisen because the framework was not applied in its entirety. Often, emphasis has been placed on Step 3 – Modelling, at the expense of the other critical steps.

The Five Phases of the In-stream Flow Incremental Methodology (IFIM) include:

Phase 1. Identifying problems

The problems are identified and broad issues and objectives are related to legal entitlement identification.

Phase 2. Project planning and catchment characterization

The technical part of the project is planned in terms of characterising the broad-scale catchment processes, species present and their life history strategies, identifying likely limiting factors, collecting baseline hydrological, physical and biological data.

Phase 3. Developing models

Models of the river are constructed and calibrated. IFIM distinguishes between microhabitat, commonly modelled using an approach such as PHABSIM, and macro-habitat, which includes water chemistry/quality and physico-chemical elements such as water temperature. A structure for specifying channel and floodplain maintenance flows is present, but there is little guidance on specific methods. Hydrological models of alternative scenarios, including a baseline of either naturalised or historical conditions, drive the habitat models. The models are integrated, using habitat as a common currency.

Phase 4. Formulating and testing scenarios

Alternative scenarios of dam releases or abstraction restrictions are formulated and tested using the models to determine the impact of different levels of flow alteration on individual species, communities or whole ecosystems.

Phase 5. Providing inputs into negotiations

The technical outputs are used in negotiations between different parties to resolve the issues set out in step one.

3.2.5.2 Downstream response to imposed flow transformation (DRIFT)

The Downstream Response to Imposed Flow Transformation (DRIFT) framework (King et al., 2003) was developed in South Africa. It is scenario-based, providing decision-makers with options (scenarios) of future flow regimes for the river of concern, together with the consequences for the condition of the river. Probably it's most important and innovative feature is a strong socio-economic module, which describes the predicted impacts of each scenario on subsistence users of the resources of a river.

DRIFT has four modules:

(i) **Biophysical:** Within the constraints of the project, scientific studies are made in all aspects of the river ecosystem: hydrology, hydraulics, geomorphology, water quality, riparian trees and aquatic and fringing plants, aquatic invertebrates, fish, semi-aquatic mammals, herpetofauna and microbiota. All studies are linked to flow;

so as to predict how any part of the ecosystem will change in response to specified changes in flow.

(ii) **Socio-economic:** Social studies are made of all river resources used by common property users for subsistence, and the river-related health profiles of these people and their livestock. The resources used are costed. All studies are linked to flow, to predict how the people will be affected by specified river changes.

(iii) **Scenario-Building:** For any future flow regime the client would like to consider that the predicted change in condition of the river ecosystem is described using the database created in module (i) and (ii). The predicted impact of each scenario on common property subsistence users is also described, together with its uncertainty. DRIFT provides a routine for optimizing the flow regime that gives maximum benefits for a given volume of water available.

(iv) **Economics:** The compensation costs of each scenario for common property users are calculated.

If there are no common property subsistence users, modules (ii) and (iv) can be omitted. Although DRIFT is usually used to build scenarios, its database can equally be used to set flows for achieving specific objectives. The DRIFT Solver can optimize ecological condition through combinations of dam releases of different timings, magnitudes and durations, given a set annual environmental allocation of water.

3.2.5.3 Building block methodology (BBM)

The Building Block Methodology was developed by South African water scientists (King and Tharme, 1994 and King and Louw, 1998). There are three major assumptions underlying the methodology:

1. The riverine biota can cope with naturally occurring baseflow conditions but may be reliant on other higher flow conditions in order to fulfil important life history needs.
2. The identification and incorporation of these important flow characteristics will help to maintain the river's natural biota and processes.
3. Certain flows influence channel morphology more than others and their incorporation into a modified flow regime will aid maintenance of natural channel structure and the diversity of the physical biotopes within the river (King and Tharme 1994; Tharme 1996).

The objective of the Building Block Methodology is to determine ecologically acceptable, modified flow regimes for impounded rivers and other situations where flows are regulated. Application of the methodology provides advice on the IFR of a river through a systematic sequence of activities involving three main phases:

1. A comprehensive information gathering phase undertaken by experts in their fields (fluvial geomorphology, hydraulic modelling, aquatic ecology, aquatic chemistry, hydrology, water engineering, social and recreational aspects). Coordination of activities is achieved through an IFR planning meeting, and this phase of the BBM culminates in a comprehensive 'Starter Document' provided to all participants prior to a structured IFR workshop. Pre-workshop activities also involve the selection of IFR sites. They are selected to capture and represent spatial geomorphological and biological variation along the river and its major tributaries. The Starter Document serves to achieve three objectives: it informs all participants about the river; it encourages the experts to focus on the river's flow requirements; and it remains as a lasting synthesis of knowledge on a specific river at a specific time (King and Tharme, 1994).
2. The IFR workshop generally involves about 20 people, representing agency water managers and engineers, the consulting engineers appointed for the specific development, and the disciplinary experts. The workshop commences with a rapid overview of the Starter Document and, usually, a field visit to each instream flow site along the river. A chairperson and facilitator then guide the workshop participants through the various steps of the Building Block Methodology to reach a consensus on a recommended modified flow regime for the river. This is based on monthly flows and special purpose flows over shorter time spans, each component of flow being specified in terms of magnitude, time of year, duration, and rate of rise and fall of flood flows. Flow regimes are developed for river maintenance and for drought conditions.

   A 'motivation' is provided for each specified flow by its proponent, and these are recorded in workshop report. Recommendations are designed to achieve a particular 'desired future state' for the river along each reach, given its existing ecological condition and the importance of the reach and river in the broader context of riverine conservation and social uses of the river (King and Louw, 1998). The construction of flow regime is quantitative in that conversion of much of the ecological knowledge about the river into recommended environmental flows depends on accurate river cross-sections and stage-discharge rating curves, while recommendations for certain high flows depend on accurate hydrological data (King and Tharme, 1994).

   Each workshop takes two to four days, depending upon the size of the catchment, its geomorphological and ecological heterogeneity, and the number and location of proposed water developments. A technical report is produced after the workshop, recording the processes used, the inputs of experts, and the outcomes in terms of in-stream flow recommendations.
3. The third phase constitutes a series of activities that link the environmental flow considerations to the engineering activities taking place in the catchment. Hydrological yield analysis, assessment of conflicts with potential consumptive users, and a coarse flow-related assessment of the implications of IFR recommendations for the complete river system are combined to produce a description of the 'working guide desired state', with its IFR (King and Louw, 1998). Two or three other possible states which would require more or less water than the IFR are also described, each linked to its probable

physical, ecological, social and economic consequences. Outcomes from these assessments are then linked to a public participation process, ending with a decision on whether or not the project will proceed and the IFR will be met. If the project proceeds with agreement to meet the IFR, planners use the IFR tables to reserve water for the river (King and Louw, 1998).

3.2.5.4 Ecological limits of hydrological alteration (ELOHA)

A new framework known as Ecological Limits of Hydrologic Alteration (ELOHA) has been proposed by a group of scientists (Poff et al., 2009) offering a flexible, scientifically defensible compromise for broadly assessing environmental flow needs when there are limited in-depth studies in a region. ELOHA builds upon the knowledge gained from past river-specific studies. This knowledge is applied to geographic areas such as a state, or a large river basin. ELOHA synthesizes existing hydrologic and ecological databases from rivers within a region to generate flow alteration-ecological response relationships for rivers with different hydrological regimes. It would be desirable that progressively more sophisticated methods are applied for EF estimation as more elaborate databases and expertize develops in a country. Such strategy would be beneficial for science, environment, and society. Recently, the Nature Conservancy recommended three levels in a hierarchical framework of development of E-Flow assessment methodologies. Level 1 includes hydrological, hydraulic and habitat simulation methodologies. At Level 2, initial flow recommendations depending primarily on the judgment of multidisciplinary expert panels which improves the basic approach from Level 1. At Level 3, the process is mainly about analyzing the tradeoffs and probable results of operational changes thus more related to the E-Flow implementation (Kendy et al., 2012). Therefore, the Nature Conservancy takes ELOHA as a Level 1 approach. Accordingly, it developed a Level 2 approach, named it "Savannah Process" as it was first implemented on the Savannah River. This involves expert workshops to recommend a set of flow releases. Monitoring of such flows may be utilized further to improve understanding of river processes and for adaptive management. This process has been carried out by the scientists and water managers in the Susquehanna (USA), Magdalena (Colombia) and Potomac (USA) river basins by expert panels to assess E-Flow needs for river types, instead of a particular river. Further, the Hydraulic Engineering Center (HEC) of the U.S. Army Corps of Engineers and The Nature Conservancy developed a Flow Regime Prescription Tool to help expert panels make E-Flow recommendations.

For the present studty, habitat simulation methodology based on Instream Flow Incremental Method (IFIM) has been selected and incorporated for the selected keystone fish species at selected locations.

3.3 COMPILATION OF DATA/INFORMATION ON BIOTIC AND ABIOTIC PARAMETERS

The contacts with eminent fish biologists were made for providing the information on the biotic parameters (abundance of aquatic species viz. phytoplanktons, zooplanktons,

macroinvertebrates and vertebrates) and influencing abiotic parameters (water depth & velocity and water quality parameters: water temperature, pH, DO, BOD, turbidity etc.). In this process, the information collected on biotic and abiotic parameters of the streams in western Himalayan region was processed. The parameters of the concurrent period were further analyzed for their variability and possibility for developing any significant relationships.

3.4 IDENTIFICATION OF SIGNIFICANT RELATIONSHIPS BETWEEN BIOTIC AND ABIOTIC PARAMETERS AND AMONG THE BIOTIC PARAMETERS

The data collected and compiled was further segregated into two groups: (i) Sites having average annual data; (ii) sites having average monthly data. Further, for both the cases, the correlaogram between abiotic and biotic parameters and also among biotic parameters were prepared. Using the t-value, the relationships with significant correlation were found out.

3.5 DEVELOPING THE HABITAT SUITABILITY CURVES FOR AQUATIC SPECIES

The selected significant relationships have been explored for various mathematical relationships viz. linear, polynomial, exponential, power etc. The relationship with best coefficient of determination was seleced.

As the habitat simulation models require the species wise habitat suitability curves for three habitat parameters viz. depth, velocity and substrate, the habitat suitability curves for the keystone species were developed using the specified module in the software 'System for Environmental Flow Assessment (SEFA)'.

3.6 ASSESSMENT OF ENVIRONMENTAL FLOWS THROUGH HABITAT SIMULATION MODELLING

Habitat simulation methodologies for E-Flow assessment are based on hydrological, hydraulic and biological response data. They model links between discharge, available habitat conditions (including hydraulics) and their suitability to target biota. Environmental flow is predicted from habitat-discharge curves or habitat time and exceedence 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, modelled 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 modelled 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 exceedence 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 meso-scale 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 River 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. For the present study, SEFA software will be applied for the E-Flow assessment.

3.6.1 Overview of System for Environmental Flows (SEFA) Software

Several recent technological and generational changes have led to the need for improved approaches to riverine habitat modeling and more comprehensive environmental flow assessments. The Instream Flow Incremental Methodology (IFIM) described an impact assessment framework but did not create the comprehensive software which would allow for a complete implementation of that framework. **SEFA, System for Environmental Flow Analysis**, is new software that implements the substance of the IFIM. SEFA has been created through a collaboration of the primary creative forces behind the principal versions of existing physical habitat simulation software. Bob Milhous (PHABSIM), Ian Jowett (RHYHABSIM), and Tom Payne (RHABSIM) have contributed their considerable experience acquired through development and use of these programs, and Juan Manuel Diez Hernández provides both his experience and Spanish-language capability. In a single Windows 7 and Windows 10 – compatible 32-bit and 64 bit programs currently available for purchase on this site, SEFA contains one dimensional habitat hydraulics analysis, habitat suitability criteria development, water temperature modeling, sediment transport analysis, dissolved oxygen modeling, riparian modeling, and time series analysis, and externally references to legal-institutional analysis and two dimensional modeling.

This new tool and a not-for-profit technical and educational support structure will ensure continuity into the future for the critical science of instream flow evaluation and

environmental flow protection. A program for converting Teledyne RD WINRIVER ADCP ascii files or EXCEL files created using SonTek RiverSurveyor Live into an EXCEL file suitable for import into SEFA is also available for download.

SEFA was developed to provide an integrated set of tools for environmental flow assessment, as envisaged in the incremental flow analysis (IFIM).

- Data and presentation
- Development of habitat suitability curves and generalized additive models
- Hydraulic habitat model
- Water surface profile model
- Sediment analyses, including flushing flows and sediment deposition
- Water temperature modeling
- Dissolved oxygen modeling
- Time series analysis, including hydraulic habitat, riparian inundation, indicators of hydrologic alteration, and event analysis

The program provides a set of tools that allows the effects of flow alteration on various physical parameters to be assessed. For example, the various outputs can be graphs or tables showing how parameters like area weighted suitability (AWS, previously called WUA), dissolved oxygen, water temperature, inundation levels and sediment functions vary with flow. Changes to the flow regime can then be further examined using time series analysis to evaluate changes in the frequency, magnitude and timing of hydrological variables and variables such as area weighted suitability and inundation.

Details of the various calculation options for experienced users of PHABSIM are also included in the model.

Data

Although it is possible to enter data directly, it is better to enter data in excel and import. In this way, you have a copy of the data in excel as well as in the SEFA rhbx file. The date entry/edit module allows data to be viewed and edited, if necessary.

Units/Date

Internally, all calculations are carried out in metric. However, results can be presented either in feet or metres. When files are imported, the units of the file will be requested, if not specified in the file.

A wide variety of date formats are recognized. Date can be in either day/month/year or month/day/year order. The default date/time presentation format is day/month/year order, but it can be changed to month/day/year order.

Import/export

Various file types can be imported and converted into a SEFA file. The types are delimited text (txt hab), excel (xls xlsx), RHYHABSIM (rhb), RHABSIM (rhb), PHABSIM DOS text (*.ifg) and PHABSIM windows files (*.phb etc.).

A SEFA file can be exported as a text file (.hab). The text file could then be imported to recreate the SEFA file. This is useful for creating a text backup of a file and its calibration. It also provides an alternative method of viewing the data, when you are familiar with the text format.

Checking data

A procedure is provided to check data and calibration. The results are listed in a text window and if there are any problems, they are shown as blue text. There are quite a number of checks. These include checking:

- substrate names that are entered against the substrate types that that the program assumes.
- rating curves.
- levels.
- % composition of substrate types sum to 100%.
- extreme of negative values of velocity.
- offsets are all in increasing or decreasing order.
- calibration gauging listing the stage change/flow change, highlighting exceptionally high or low values

Habitat Suitability Curves and Models

A separate program module is provided for the analysis of habitat suitability data and the development of habitat suitability curves and statistical models. Habitat suitability curves are imported from text files into a library.

Hydraulic/Habitat Suitability Analyses

The variation of hydraulic parameters and habitat suitability with flow can be shown at three scales, point, cross-section and reach. Most analyses can be carried out for any combination of reaches and cross-sections.

By default habitat is evaluated using depth, velocity and substrate criteria. It is possible to use any combination of these criteria. In addition, other criteria such as a substrate index or cover index can be included in the evaluation.

Fluctuating flow analysis

This produces a graph that shows how habitat reduces as the amount of flow fluctuation increases. The left axis is the area weighted suitability (AWS) and the bottom axis is the proportion of flow fluctuation.

The effect of flow fluctuations on hydraulic habitat is modeled about a base flow. The base flow is considered as the normal flow and that the fluctuation causes the flow to fall below normal and to increase above normal.

Passage analysis
The variation of passage width (total width and maximum contiguous width) with flow can be calculated.

Sediment Modeling

Flushing flow requirements can be estimated by calculating the area of stream bed flushed (deep, and surface) using Milhous flushing criteria. Velocity, shear velocity, dimensionless shear stress, suspended sediment size and bed load size can also be displayed. The % area of the river in which silt or sand will deposit can also be calculated using Shields curve for initiation of movement (i.e., movement/deposition occurs when dimensionless shear stress is 0.056.

The longitudinal variation in suspended sediment concentration can be calculated assuming no input of sediment. This models the settling process of fine particles (sticky river bed) in water following Einstein's (1968) work on siltation of redds.

Water Temperature Modeling

Two methods (Lagrangian and Theurer) can be used to calculate the variation of maximum, minimum and daily mean water temperature with distance downstream. It is also possible to use meteorological and water temperature time series data for calibration and modeling.

Dissolved Oxygen Modeling

Procedures are provided to calculate dissolved oxygen parameters (re-aeration, respiration and production) from recorded data and to use these parameters to calculate the effect of flow on dissolved oxygen.

Water Surface Profile Modeling

Procedures are provided for calibration and modeling using water surface profile modeling. The main innovation is the ability to change Manning's N with flow. And there are a number of ways of doing this (e.g., use the beta value of the first section for all, use the

calculated beta between each pair of sections, use the average beta value for all). A series of WSP profiles can be saved for as rating curves and used for subsequent analyses.

Flow Analyses

An import wizard is used to import a text or EXCEL file containing date and flow data. A wide variety of date formats are recognized. Date can be in either dd/mm/yy or mm/dd/yy order. Many of the following analyses are applicable to other types of times series data. These data can be displayed as graphs and used to calculate flow duration statistics, seasonal flow statistics and indicators of hydrologic alteration.

Similar analyses can be carried out for area weighted suitability (AWS previously called weighted usable area).

The frequency, timing and duration of riparian inundation can be calculated for a specified height above base flow.

The frequency and duration of events can be calculated. Multiple criteria can be specified for events (e.g. flow > 10 and flow < 100).

Calculation Details and PHABSIM Options

The default methods are recommended for general use, but preferences can be set to allow an emulation of IFG4 methods for Manning's N calibration, calculation of velocity and calculation of rating curves.

By default, SEFA calculates habitat suitability by interpolating linearly at between cross-section measurements points. For example if one point is measured at the water's edge and the next in the water at a depth of 0.5 m, the program will calculate habitat suitability at 0.025 m increments from 0 to 0.5 m, If this is not checked, habitat suitability will only be calculated at measurements points, as it was in PHABSIM.

Log-log rating relationships are derived for stage-discharge pairs of measurements. The default method is to fit the curve through the survey flow and the best least square fit to other stage-discharge pairs. This method is most appropriate if the survey cross-section is based on measured water depths, because it does not introduce spurious depth errors in depth when predicting water levels at the survey flow.

The alternative method is that used in IFG4 (PHABSIM) to fit the curve through all stage-discharge pairs. The default velocity calibration and prediction method is to calculate Manning's N and VDF from conveyance (a function of hydraulic radius) at measurement points. When predicting velocities for a given flow, they are calculated from conveyance and are then adjusted so that they give the given flow times the ratio of measured to survey flow.

Using this default method and the default log-log rating method predicted velocities at the survey flow will be the same as measured velocities.

The alternative method is that used in IFG4 (PHABSIM), where Manning's N values are calculated from water depth at each measurement point and the slope for the cross-section (usually the default slope of 0.0025). When predicting velocities for a given flow, they are calculated using manning's equation (N, depth and slope), with the velocities are then adjusted so that they give the given flow.

Calculation of habitat suitability.

Three methods of calculating the combined suitability index are available. The default is for CSI values to be multiplied to form a single combined index.

CHAPTER - 4
RESULTS AND DISCUSSIONS

4.1 Compilation of Data/Information on Biotic and Abiotic Parameters

The contacts with eminent fish biologists were made for providing the information on the biotic parameters (abundance of aquatic species viz. phytoplanktons, zooplanktons, macroinvertebrates and vertebrates) and influencing abiotic parameters (water depth & velocity and water quality parameters: water temperature, pH, DO, BOD, turbidity etc.). In this process, the information collected on biotic and abiotic parameters of the streams in western Himalayan region was processed. The parameters of the concurrent period were further analyzed for their variability and possibility for developing any significant relationships. The data collected and compiled for 48 locations in western Himalayan region as shown in Fig. 4.1.

The available secondary data on biotic and abiotic parameters were of two categories:

(i) Sites having average annual data of biotic and abiotic parameters

(ii) Sites having average annual data of biotic and abiotic parameters

Sites having average monthly data of biotic and abiotic parameters

Under this category, the data were collected and compiled from 5 sites on the western Himalayan streams as given in Table 4.1. Among the abiotic parameters, Altitude, Gradient (%), Air Temp (^{0}C), Water Temp (^{0}C), Water Velocity (cm/s), DO (mg/L), Conductivity (microS/cm), Turbidity (NTU), TDS (mg/L), pH, Chlorides (mg/L), Total Alkalinity (mg/L), Total Hardness (mg/L), Nitrates (mg/L), Phosphates (mg/L) were collected. Among the biotic parameters, density of Plankton, Phytobenthos, Macroinvertebrates and Fish were collected.

Table 4.1: Sites having average monthly data for the biotic and abiotic parameters

SN	Site	Longitude		Latitude		Altitude	River Basin
		Degree	Minute	Degree	Minute		
1.	Gambhar (Gambhar pul)	76	58	31	1	815	Satluj
2.	Gamrola (Gamrola bridge)	76	55	31	35	710	Satluj
3.	Seer (Ghumarwin)	77	1	31	25	580	Satluj
4.	Suketi (Chakkar, Mandi)	76	58	31	43	754	Beas
5.	Sainj (Larrji)	77	6	31	58	957	Beas

Sites having average annual data of biotic and abiotic parameters

Under this category, the data were collected and compiled from 48 sites on the western Himalayan streams viz. tributaries of Ravi, Beas, Satluj, Ghaggar, Yamuna and Ganga (Table 4.2). Among the abiotic parameters, Gradient (%), Air Temp (^{0}C), Water Temp (^{0}C), Water Velocity (cm/s), DO (mg/L), Conductivity (microS/cm), Turbidity (NTU), TDS (mg/L), pH,

Chlorides (mg/L), Total Alkalinity (mg/L), Total Hardness (mg/L), Nitrates (mg/L), Phosphates (mg/L) were collected. Among the biotic parameters, density of Phytoplankton, Zooplankton, Benthos, Fish, Vertebrates were collected.

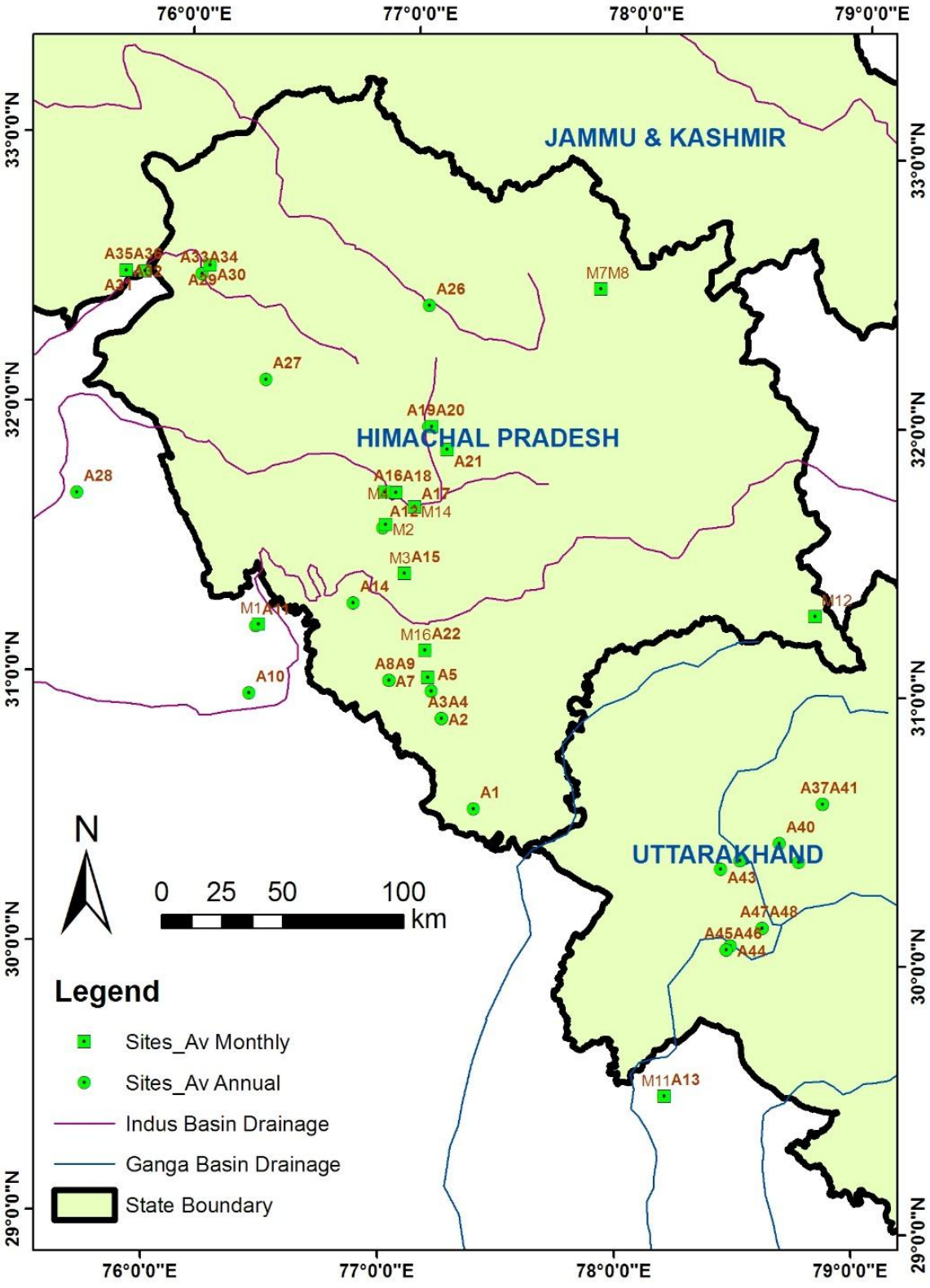


Fig. 4.1: Locations of biotic and abiotic data availability for the concurrent periods

Table 4.2: Sites having average annual data for the biotic and abiotic parameters

SN	Site	Longitude		Latitude		Altitude	River Basin
		Degree	Minute	Degree	Minute		
1.	Markanda (Khadir ka bagh)	77	21	30	33	500	Ghaggar
2.	Giri (Yashwantnagar)	77	12	30	53	900	Yamuna
3.	Giri (Gaura)	77	12	30	53	900	Yamuna
4.	Ashni (Gaura)	77	12	30	53	900	Yamuna
5.	Ashni (Sadhopul)	77	9	30	59	1130	Yamuna
6.	Kaushalya (Chakkimor)	70	0	30	51	500	Ghaggar
7.	Dabar (Dev Bhoomi, Subathu)	76	58	31	1	820	Satluj
8.	Kuthar (Gambhar pul, Subathu)	76	58	31	1	810	Satluj
9.	Gambhar (Gambhar pul)	76	58	31	1	815	Satluj
10.	Baddi (Baddi)	76	22	30	57	400	Ghaggar
11.	Gambhar (Gambhar bridge)	76	23	31	12	600	Satluj
12.	Gamrola (Gamrola bridge)	76	55	31	35	710	Satluj
13.	Dehni (Dehni-Massewal)	78	12	29	30	390	Satluj
14.	Ali (Jabal, Bilaspur)	76	48	31	18	650	Satluj
15.	Seer (Ghumarwin)	77	1	31	25	580	Satluj
16.	Jarol (Harabag, Mandi)	76	55	31	43	750	Satluj
17.	Jeuni (Pandoh)	77	3	31	40	850	Beas
18.	Suketi (Chakkar, Mandi)	76	58	31	43	754	Beas
19.	Tirthan (Larji)	77	6	31	58	957	Beas
20.	Sainj (Larrji)	77	6	31	58	957	Beas
21.	Parvati (Chharol, Kullu)	77	11	31	53	1115	Beas
22.	Sarvari (Kullu)	77	7	31	8	1245	Beas
23.	Faujat (Dwara village, Kullu)	77	8	31	2	1433	Beas
24.	Kahn (Sansarpur terrace, Kangra)	70	35	31	40	400	Beas
25.	Ghatti (Ghatti, Kangra)	70	35	31	42	400	Beas
26.	Baner (Haripur, Kangra)	77	5	32	25	500	Beas
27.	Gaj (Nagrota Surian, Kangra)	76	23	32	7	430	Beas
28.	Dehar (Jwali, Kangra)	75	35	31	40	400	Beas
29.	Sal Khad (u/s)	76	7	32	32	910	Ravi
30.	Sal Khad (d/s)	76	7	32	32	880	Ravi
31.	Naini Khad (u/s)	75	45	32	30	1115	Ravi
32.	Naini Khad (d/s)	75	45	32	30	850	Ravi
33.	Chaned Khad (u/s)	76	5	32	30	1150	Ravi
34.	Chaned Khad (d/s)	76	5	32	30	910	Ravi
35.	Panjpula (u/s)	75	45	32	30	1056	Ravi
36.	Panjpula (d/s)	75	45	32	30	900	Ravi
37.	Balganga (u/s)	78	51	30	36	1524	Ganga
38.	Balganga (d/s)	78	30	30	23	1100	Ganga
39.	Nailchami (u/s)	78	45	30	23	1174	Ganga
40.	Nailchami (d/s)	78	40	30	27	974	Ganga
41.	Bhilangna (u/s)	78	51	30	36	974	Ganga
42.	Bhilangna (d/s)	78	30	30	23	772	Ganga
43.	Henvel (u/s)	78	25	30	21	700	Ganga
44.	Henvel (d/s)	78	28	30	4	380	Ganga
45.	Gular (u/s)	78	27	30	3	400	Ganga
46.	Gular (d/s)	78	27	30	3	380	Ganga
47.	Bharpur Ka Gadera (u/s)	78	36	30	8	440	Ganga
48.	Bharpur Ka Gadera (d/s)	78	36	30	8	420	Ganga

4.2 Identification of Significant Relationships between Biotic and Abiotic Parameters and among the Biotic Parameters

Sites having average monthly data of biotic and abiotic parameters

The abiotic and biotic parameters compiled for 5 sites have been used for calculation of correlation between abiotic and biotic parameters and also among biotic parameters. The correlograms so obtained are shown in Tables 4.3 and 4.4. Further, these values have been tested for significance as shown in Tables 4.5 and 4.6.

Table 4.3: Correlogram between average monthly abiotic and biotic parameters

	Water Temp (0C)	Water Velocity (cm/s)	Conductivity (microS/cm)	Turbidity (NTU)	pH	Chlorides (mg/L)	Total Alkalinity (mg/L)	Total Hardness (mg/L)	Nitrates (mg/L)	Phosphates (mg/L)	Silicates (mg/L)	DO (mg/L)
Plankton	-0.027	-0.531	0.589	-0.211	0.563	0.258	0.346	0.582	0.152	-0.206	0.431	0.212
Phytobenthos	-0.057	-0.562	0.537	-0.219	0.532	0.262	0.322	0.544	0.187	-0.262	0.416	0.248
Macroinvertebrates	-0.149	-0.455	0.445	-0.218	0.625	0.198	0.370	0.451	0.219	-0.073	0.446	0.334
Fish	0.371	-0.496	0.527	-0.261	0.452	0.273	0.609	0.479	0.259	-0.347	0.254	-0.206

Table 4.4: Correlogram among average monthly biotic parameters

	Plankton	Phytobenthos	Macroinvertebrates	Fish
Plankton	1.000	0.956	0.701	0.392
Phytobenthos	0.956	1.000	0.704	0.405
Macroinvertebrates	0.701	0.704	1.000	0.377
Fish	0.392	0.405	0.377	1.000

Table 4.5: Significance of correlation between average monthly abiotic and biotic parameters at 5% significance level

	Water Temp (0C)	Water Velocity (cm/s)	Conductivity (microS/cm)	Turbidity (NTU)	pH	Chlorides (mg/L)	Total Alkalinity (mg/L)	Total Hardness (mg/L)	Nitrates (mg/L)	Phosphates (mg/L)	Silicates (mg/L)	DO (mg/L)
Plankton	S	NS	NS	S	NS	NS	NS	NS	S	S	NS	S
Phytobenthos	S	NS	NS	S	NS	NS	NS	NS	S	NS	NS	S
Macroinvertebrates	S	NS	NS	S	NS	S	NS	NS	S	S	NS	NS
Fish	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	S

NS: Non-Significant; S: Significant

Table 4.6: Significance of correlation among average monthly biotic parameters at 5% significance level

	Plankton	Phytobenthos	Macroinvertebrates	Fish
Plankton	-	NS	NS	NS
Phytobenthos	NS	-	NS	NS
Macroinvertebrates	NS	NS	-	NS
Fish	NS	NS	NS	-

NS: Non-Significant; S: Significant

It is clearly observed from the above tables that Plankton density has been found significant with water temp., turbidity, nitrates, phosphates and DO. Phytobenthos density has been found significant with water temp., turbidity, nitrates, phosphates and DO. Macroinvertebrates density was found significant with water temp., tubidity, chlorides, nitrates and phosphates. Fish density has been found signicant with DO.

Sites having average annual data of biotic and abiotic parameters

The abiotic and biotic parameters compiled for 48 sites have been used for calculation of correlation between abiotic and biotic parameters and also among biotic parameters. The correlograms so obtained are shown in Tables 4.7 and 4.8. Further, these values have been tested for significance as shown in Tables 4.9 and 4.10.

Table 4.7: Correlogram between average annual abiotic and biotic parameters

	Water Temp (0C)	Water Velocity (cm/s)	DO (mg/L)	Conductivity (microS/cm)	Turbidity (NTU)	pH	Chlorides (mg/L)	Total Alkalinity (mg/L)	Total Hardness (mg/L)	Nitrates (mg/L)	Phosphates (mg/L)
Phytoplankton	0.328	-0.090	-0.312	-0.021	-0.030	0.148	-0.339	0.061	-0.001	0.191	-0.157
Zooplankton	0.581	-0.344	-0.177	0.381	-0.263	0.447	0.108	0.423	0.353	0.269	-0.128
Benthos	0.185	0.003	-0.309	-0.130	-0.034	0.089	-0.386	-0.106	-0.063	-0.006	-0.133
Fish	0.591	-0.198	-0.210	0.439	-0.017	0.343	0.229	0.507	0.402	0.388	0.116
Vertebrates	0.645	-0.283	-0.175	0.606	-0.048	0.514	0.157	0.640	0.602	0.456	0.068

Table 4.8: Correlogram among average annual biotic parameters

	Phytoplankton	Zooplankton	Benthos	Fish	Vertebrates
Phytoplankton	1.000	0.394	0.891	0.386	0.291
Zooplankton	0.394	1.000	0.346	0.662	0.551
Benthos	0.891	0.346	1.000	0.172	0.134
Fish	0.386	0.662	0.172	1.000	0.678
Vertebrates	0.291	0.551	0.134	0.678	1.000

Table 4.9: Significance of correlation between average annual abiotic and biotic parameters at 5% significance level

	Water Temp (0C)	Water Velocity (cm/s)	DO (mg/L)	Conductivity (microS/cm)	Turbidity (NTU)	pH	Chlorides (mg/L)	Total Alkalinity (mg/L)	Total Hardness (mg/L)	Nitrates (mg/L)	Phosphates (mg/L)
Phytoplankton	NS	S	NS	S	S	S	NS	S	S	S	S
Zooplankton	NS	NS	S	NS	S	NS	S	NS	NS	S	S
Benthos	S	S	NS	S	S	S	NS	S	S	S	S
Fish	NS	S	S	NS	S	NS	S	NS	NS	NS	S
Vertebrates	NS	S	S	NS	S	NS	S	NS	NS	NS	S

NS: Non-Significant; S: Significant

Table 4.10: Significance of correlation among average annual biotic parameters at 5% significance level

	Phytoplankton	Zooplankton	Benthos	Fish	Vertebrates
Phytoplankton	-	NS	NS	NS	NS
Zooplankton	NS	-	NS	NS	NS
Benthos	NS	NS	-	S	S
Fish	NS	NS	S	-	NS
Vertebrates	NS	NS	S	NS	-

NS: Non-Significant; S: Significant

It is visible from the above tables that Phytoplankton density has been found significant with water temp., water velocity, conductivity, turbidity, pH, alkalinity, hardness, nitrates and phosphates. Zooplankton density has been found significant with DO, turbidity, chlorides, nitrates and phosphates. Benthos density has been found significant with water temp., water velocity, conductivity, turbidity, pH, alkalinity, hardness, nitrates and phosphates. Fish density has been found significant with water velocity, DO, turbidity, chlorides and phosphates. Density of other vertebrates was found significant with water velocity, DO, turbidity, chlorides and phosphates.

4.3 Developing the Habitat Suitability Curves for Aquatic Species

The selected significant relationships have been further examined for various mathematical relationships viz. linear, polynomial, exponential, power etc. The relationship with best coefficient of determination was finalized. Finally selected relationships between abiotic and biotic parameters and among biotic parameters are summarized in Table 4.11. As the environmental flow assessment is generally based on the habitat requirement of umbrella species (generally, fish), the relationships between abiotic parameters and fish diversity index has been selected for further use. It is to be noted here that fish diversity is also significantly related with benthos density, hence, relationships between parameters significant with benthos density and fish diversity index have also been selected for further analysis.

These relationships were not found physically properly representing the actual behavior observed in the field as evidenced in the literature. Moreover, the habitat simulation models require habitat suitability curves for the keystone aquatic species for three habitat parameters viz. depth, velocity and substrate. The habitat suitability curves for the use in the habitat simulation modelling were estimated using the specific module in the SEFA software as elaborated in the following sub-sections.

4.3.1 Selection of the Keystone Species for Development of Habitat Suitability Curves

The presence of a species in a particular stretch as a dominant species indicated the suitability of the region for their sustenance, growth; migration and compatibility with substrate and overbearing influence on others have been referred as focal species. They are categorized

as indicator, characteristic, keystone, flagship or umbrella species. The following literature has been reviewed to conclude on the keystone species in the western Himalayan region.

Table 4.11: Relationships between abiotic parameters and fish diversity index

Using Average Monthly Data	
Fish Diversity Index (y) DO (x)	$y = -0.76\ln(x) + 2.472$
Using Average Annual Data	
Parameters significantly related with Fish Diversity Index	
Fish Diversity Index (y) vs Water Velocity (x)	$y = 9.073e^{-0.08x}$
Fish Diversity Index (y) vs DO (x)	$y = 384.5e^{-0.55x}$
Fish Diversity Index (y) vs Turbidity (x)	$y = 2.734x^{0.276}$
Fish Diversity Index (y) vs Chloride (x)	$y = 0.009x^2 – 0.214x + 6.195$
Fish Diversity Index (y) vs Phosphate (x)	$y = 7.318x^{0.212}$
Fish Diversity Index (y) vs Benthos Density (x)	**$y = 8.125x^{0.411}$**
Parameters significantly related with Benthos Density	
Fish Diversity Index (y) vs Water Temp. (x)	$y = 0.002x^{2.560}$
Fish Diversity Index (y) vs Conductivity (x)	$y = -4E\text{-}05x^2 + 0.034x + 0.819$
Fish Diversity Index (y) vs pH (x)	$y = 6E\text{-}10x^{10.71}$
Fish Diversity Index (y) vs Total Alkalinity (x)	$y = 0.076x^{0.858}$
Fish Diversity Index (y) vs Total Hardness (x)	$y = 2.940\ln(x) – 7.436$
Fish Diversity Index (y) vs Nitrate (x)	$y = 8.125x^{0.411}$

In the Upper Ganga Basin the stretch between Gangotri to Gangnani and Mana to Vishnuprayag is considered as no fish zone. Brown trout (Salmo trutto fario) is the only fish observed by Nautiyal et al. (2007) at Jhala downstream of Bhaironghati i.e between Gangotri to Gangnani. It has been considered as keystone species for the present study. In the stretch between Gangnani to Devprayag, and Vishnuprayag to Devprayag the trouts constitute thecharacteristic fish group represented by nine species of genera Schizothorax and Schizothoracthys of which Schizothorax richardsonii (snow trout) has been identified as thekeystone species.In the stretch between Devprayag to Haridwar, the mostconspicuous group is Mahseer, represented by 2 species of Genus Tor. Tor putitora (goldenmahseer) has been referred as keystone species. The flow requirements (Depth and Velocity) of Salmo trutto fario, Schizothorax richardsonii and Tor putitora are given below (Table 4.12):

Reported optimum ranges for various microhabitat characteristics important for spawning of brown trout include water depth (23-215 cm) by Wollebaek et al. (2008) while Raleigh et al. (1986) reported that the minimum depth brown trout will spawn in is 15 cm. Water velocity preferences for brown trout spawning were reported to be 2-124 cm/s by Wollebaek et al. (2008) while Raleigh et al. (1986) reported an optimum range spawning velocity range of 40-70 cm/s and a total spawning velocity range of 13.7-90 cm/s.

Previous research has indicated that the optimal velocity range for wintering brown trout is 5.7-16 cm/s, optimal depth range of 50- 75 cm, and optimal substrate type ranging from sand to boulders (Cunjak and Power, 1986).

Table 4.12: Flow requirements of Salmo trutto fario, Schizothorax richardsonii and Tor putitora

Zone	Keystone species	Depth Requirement (m)				Velocity requirement (m/sec)			
		Adults	Juvenile	Spawning	Incubation and Larval development	Adults	Juvenile	Spawning	Incubation and larval development
Gangotri-Gangnani	Salmo trutto fario (Brown trout)	0.1-1.7	0.50-0.75	0.12-0.91	>0.30	0-0.21	0.15	0.39	0.15
Gangnani-Devprayag	Schizothorax richardsonii (Snow trout)	>0.5	0.1-1	0.5-1.00	0.1-1.00	0.5-1.5	0.5-1.0	0.5-1.0	0.1-0.5
Vishnuprayg-Devprayg									
Devprayag-Haridwar	Tor putitora (Mahseer)	>1	0.75-1.5	0.5-2.00	0.3-2.00	0.5-1.5	0.1-1.5	0.1-1.0	0.1-0.5

(Source: Nautiyal et al. 2007, Raleigh et al. 1986, Rajvanshi et al. 2012)

The biodiversity of different stretch of the same river is highly variable due to river conditions. Most of the biological communities are well adapted to the extreme flows also but in order to maintain the rich aquatic biodiversity various factors are taken into consideration i.e. water quality, flow, depth and velocity. The movement of water across the landscape influences the ecology of rivers across a broad range of spatial and temporal scales (Vannote et al., 1980; Junk et al., 1989; Poff and Ward, 1990; Poff et al., 1997; Sparks, 1995). The shape and size of river channels, the distribution of riffle and pool habitats, and the stability of the substrate are all largely determined by the interaction between the flow regime and local geology and landform (Frissel et al., 1986; Cobb et al., 1992; Newbury and Gaboury, 1993).

The estimates of flows required for keystone fishes is significantly more as compared to other biota, so if the requirement of water are satisfied for fish the needs for others will be automatically satisfied (Mathur and Kapoor, 2015).

The Himalayan fish spend the major part of their life facing the current. This helps them in two ways: firstly, to maintain their upright position, and secondly, to make respiration easier. They have to open their mouths to take in water and boost the respiratory current. The fast-swimming species of mahseer, trout and schizothoracines expend much energy in maintaining an upright position in the turbulent and fast current (Sehgal, 1988b). This means that they have

less energy available for other physiological requirements as respiration and feeding. This is aided by the flowing waters of the Himalayan streams with high Dissolved Oxygen (DO) content, which makes respiration easier. Food particles also enter the mouth with the current and it is one of the unique energy efficient feeding strategies of coldwater fishes.

Water temperature is always an important limiting factor affecting geographical distribution and local occurrence within one water system. Cold stenothermic (cannot tolerate high fluctuations in temperature) species such as the endemic Schizothorax richardsoniiand exotic brown trout (Salmo trutto fario) have an upper tolerance around 20°C. Mahseers has a wider tolerance and even survive water temperatures over 25°C. Schizothoracines and brown trout remain active in the near-zero temperature which prevail in streams of the lesser and Greater Himalaya during December and January (Sehgal, 1970). Coldwater fishes have a requirement of high DO concentration. The optimum DO concentration required for coldwater fishes is 7.0-8.0 ppm (Sehgal, 1988b). Water flow is critical in the sense that optimal velocity of water favours the growth of fish food organisms like periphyton. Stagnant waters act as a heat trap and have high water temperature as compared to flowing waters. The fast flowing waters of the Himalayan streams brings in the ice-melt cold water from the upstreams and the continuous mixing keeps the temperature within the tolerance limit of these species. Low temperature again has a positive impact on the DO concentration of water as DO and temperature are inversely related. Moreover flowing waters has high DO concentration in general. Another important feature to be considered are the life history activities of fishes and more particularly, spawning. The fertilized eggs of coldwater fishes remains adhered to the substratum. Flow of water is an important aspect in determining the subsequent spawning of eggs and survival of larvae. Water flow is critical as it prevents deposition of sediments over the eggs and enhances the oxygen supply. Flushing flows maintain the quality of spawning gravel scouring the fine sediments away.In general there is a relationship between fish body length and the water depth requirement i.e. bigger the fish, deeper the habitat requirement (Schlosser, 1987b; Humphries and Walker, 2013). Smith and Brown (2002) studied the relationship between mean depth and maximum body size of fishes and found that large sized fishes are found at greater depth. High water levels create inundated areas that fish may utilize (Keith, 1975), whereas low water surface levels may limit fish movements, available habitat, or degrade water quality (Albanese, 2001). The velocity depends on slope and gradient and cannot be controlled so depth becomes the critical controlling factor (Mathur and Kapoor, 2015).

According to the previous studies the only taxa reported in the stretch between Mana to Vishnuprayag is Phytoplanktons. So the recommended depth and velocity requirement as per our understanding for phytoplanktons in this particular stretch is about 25 cm and 0.87 m/sec respectively. The common size of brown trout (Salmo trutto fario) is about 72 cm and snow trout (Schizothorax richardsonii) is about 60 cm. The Mahseer (Tor putitora) attains a size of about 1 m. Keeping in mind the length and lifecycle of the keystone species the stretch wise recommended flow requirements (Minimum Depth and Velocity) as per our understanding for the keystone species are given below. These recommendations are based on

previous studies and a degree of subjectivity may be involved. Since there is a lack of studies and data, it is important that field investigations are launched in future to arrive at improved estimates for the study area. The recommendations on flow requirements of key stone species are given Table 4.13.

Table 4.13: Recommended Flow requirements for keystone fish species

Zone	**Keystone species**	**Depth Requirement (m)**		**Velocity Requirement (m/sec)**	
		Lean period	Spawning period	Lean period	Spawning period
		(Nov-May)	(June-Oct)	(Nov-May)	(June-Oct)
		(D1)	(D2)	(V1)	(V2)
Gangotri-Gangnani	Salmo trutto fario (Brown trout)	0.5	0.75	0.15	0.40
Gangnani-Devprayag	Schizothorax richardsonii (Snow trout)	0.5	1.0	0.5	1.0
Vishnuprayag-Devprayag					
Devprayag-Haridwar	Tor putitora (Mahseer)	0.5	1.2	0.5	1.0

(Source: Jain et al., 2014)

These recommendations are for the main river only. In small tributaries along Devprayag-Haridwar stretch, there may not be sufficient water to ensure the recommended depth. Hence the requirements may be lesser than that is recommended for the main river.

With limited data available, the depth requirement and velocity requirement suggested for the sustenance of aquatic life in the Satluj basin (Source: DCFR, Bhimtal) are given in Table 4.14.

Table 4.14: Depth and velocity requirement suggested for the sustenance of aquatic life in the Satluj basin

Zone/ Site	**Depth Requirement** (m)	**Velocity Requirement** (m/sec)
	0.2-0.3	0.1-0.15
Rampur	0.3-0.4	0.15-0.20
Kol dam	0.3-0.4	0.15-0.20
Baspa	0.2-0.3	0.1-0.15
Bhaba Khad	0.2-0.3	0.1-0.15
Ghanvi Khad	0.2-0.3	0.1-0.15

Based on the literature available, it was concluded that the keystone species for different regions of western Himalaya are as follows:

Keystone/Umbrella species for Different Zones		
Upper Zone (Epirithron) : > 1500m Brown Trout (Salmo trutto fario)	Middle Zone (Metarithron): 500-1500m Snow Trout (Schizothorax richardsonii)	Lower Zone (Hyporithron): < 500m Golden Mahseer (Tor putitora)

4.3.2 Development of Habitat Suitability Curves for the Keystone Species

The data on abundance of these aquatic species and concurrent abiotic data related to depth and velocity have been used to develop the habitat suitability curves using the specific module in SEFA software. Thus developed habitat suitability curves for the keystone species are shown in Fig. 4.2.

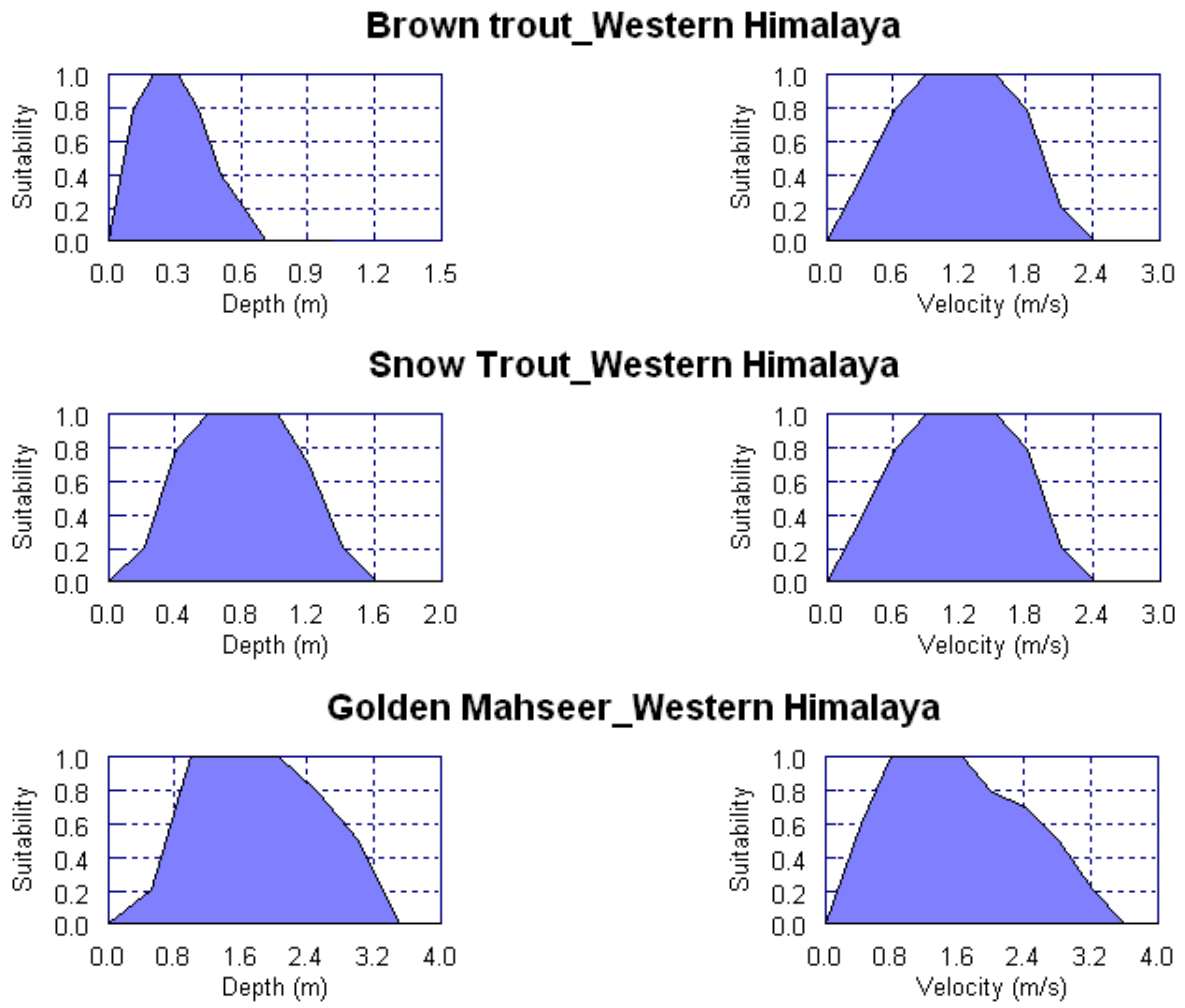


Fig. 4.2: Habitat suitability curves for the keystone species

4.4 ASSESSMENT OF ENVIRONMENTAL FLOWS USING HABITAT SIMULATION MODELLING

4.4.1 Selection of Sites for E-Flow Assessment

As the identified keystone species in the western Himalayan region belong to the regions of different altitudes, the sites for habitat simulation modelling have been selected accordingly as follows:

Selection of Sites for Different Zones		
Upper Zone (Epirithron) : > 1500m Joshimath	Middle Zone (Metarithron): 500-1500m Rudraprayag (before confluence)	Lower Zone (Hyporithron): < 500m Rishikesh

4.4.2 SEFA Model Setup and Simulations

The habitat suitability curves, discharge data, cross-section data for the selected sites and selected keystone species have been used to set up the model. The main output of the model is the area weighted suitability in terms of area per unit length of stream which is suitable for the sustenance of particular species. The simulated values of depth, velocity, wetted perimeter and area weighted suitability are shown in Fig. 4.3 to 4.18.

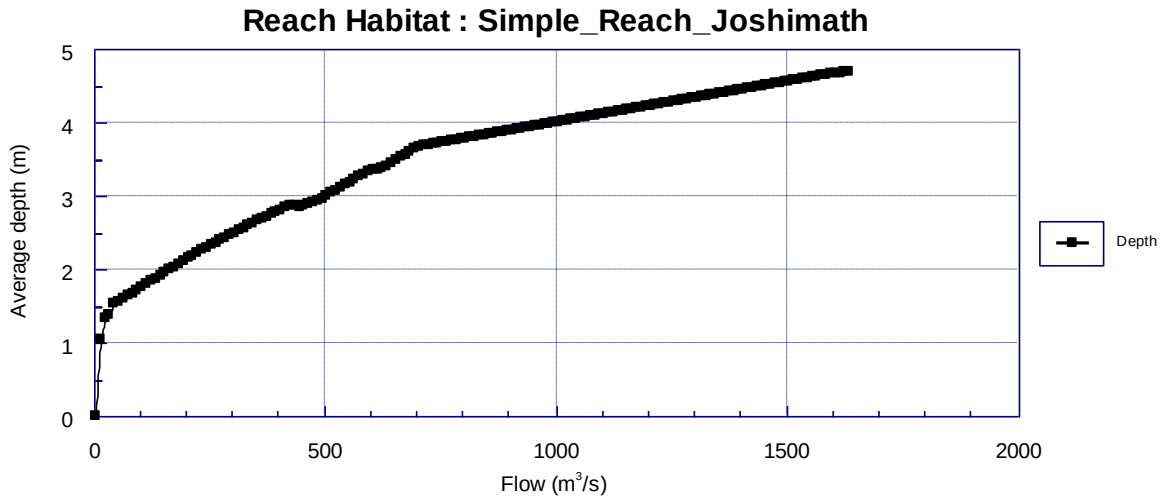


Fig. 4.3: Simulated average water depth for the historical flows at Joshimath

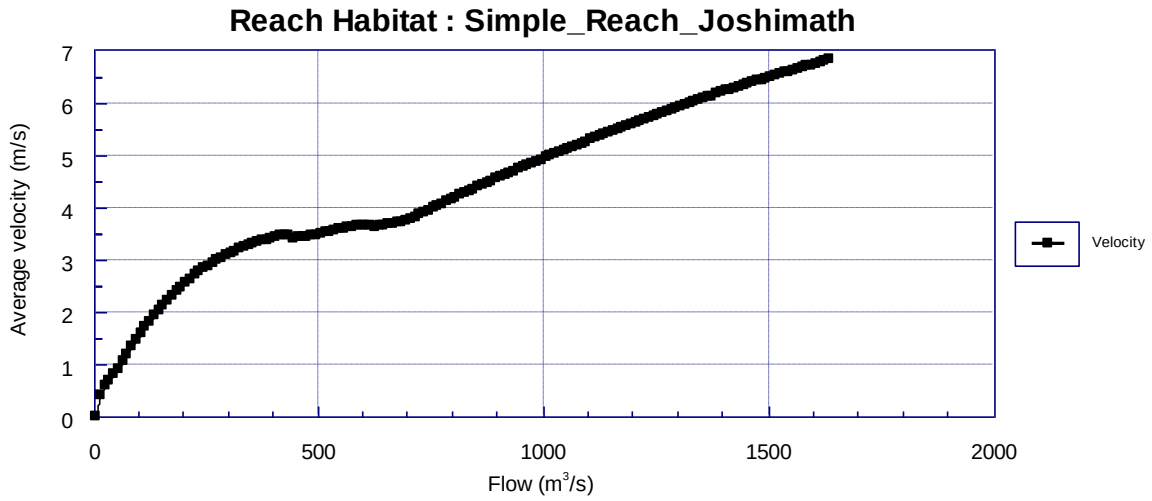


Fig. 4.4: Simulated average water velocity for the historical flows at Joshimath

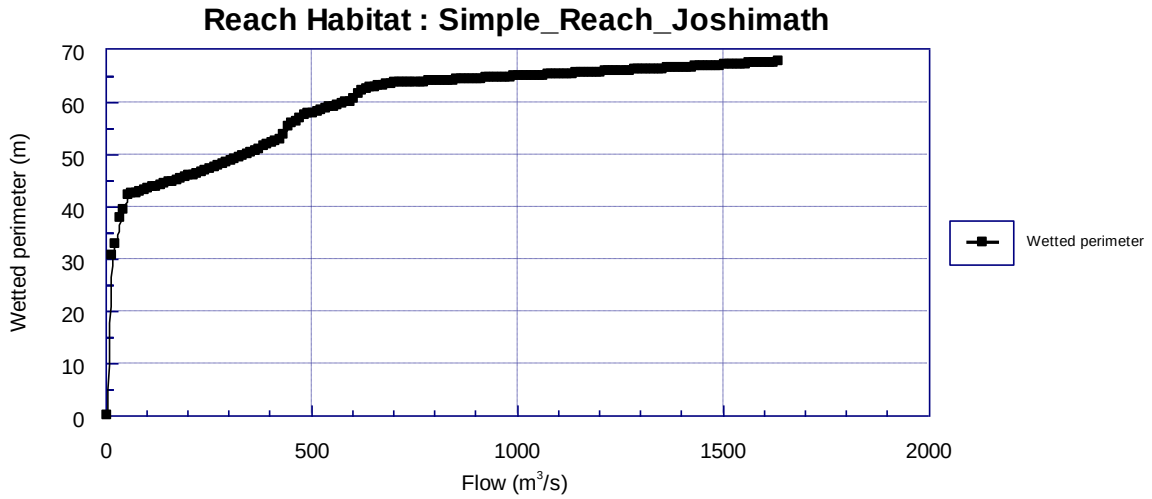


Fig. 4.5: Simulated wetted perimeter for the historical flows at Joshimath

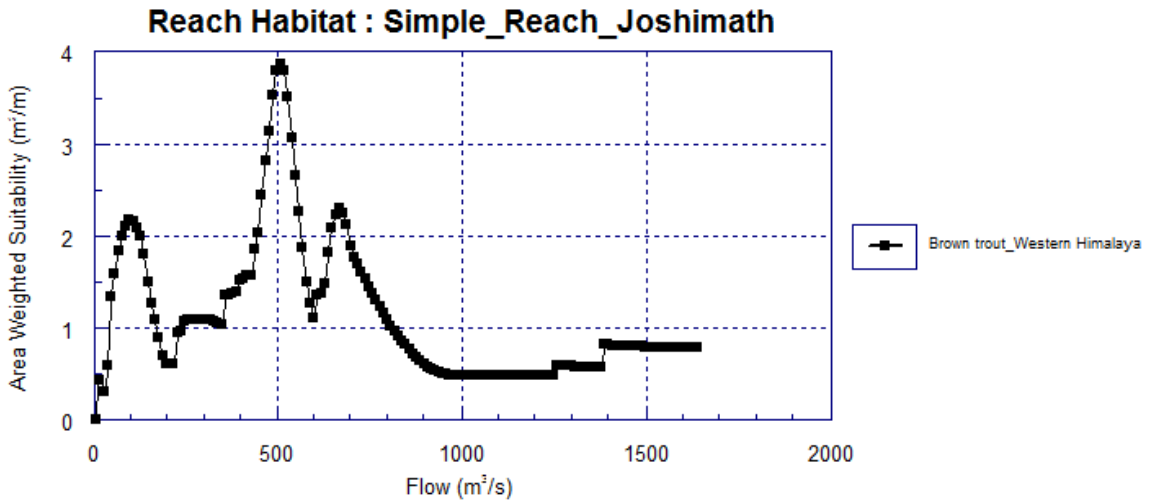


Fig. 4.6: Simulated area weighted suitability for the historical flows at Joshimath

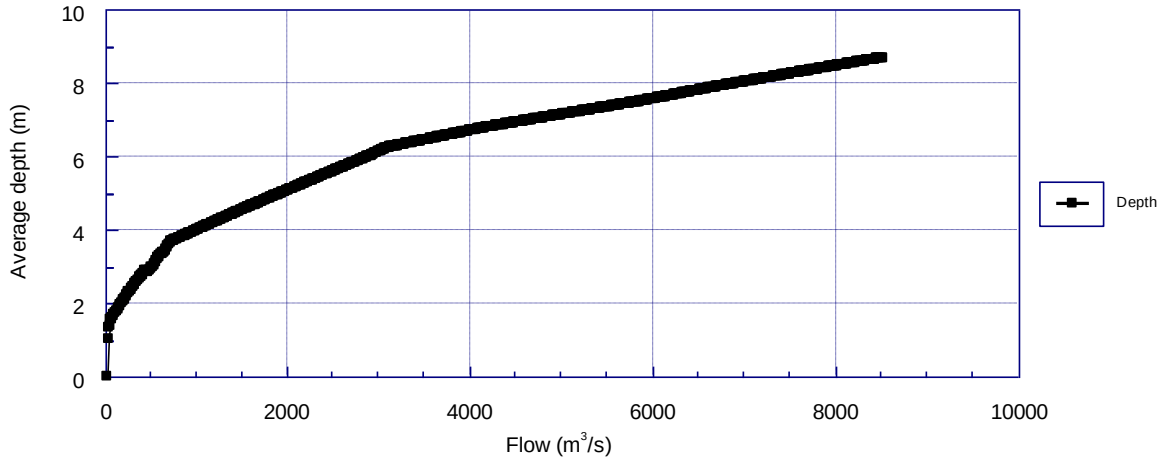


Fig. 4.7: Simulated average water depth for the historical flows at Rudraprayag (before confluence)

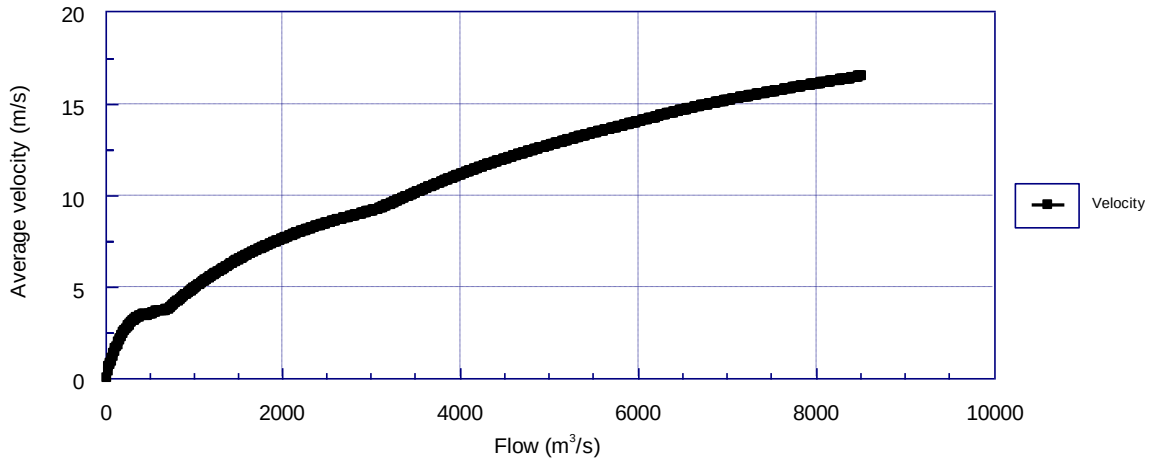


Fig. 4.8: Simulated average water velocity for the historical flows at Rudraprayag (before confluence)

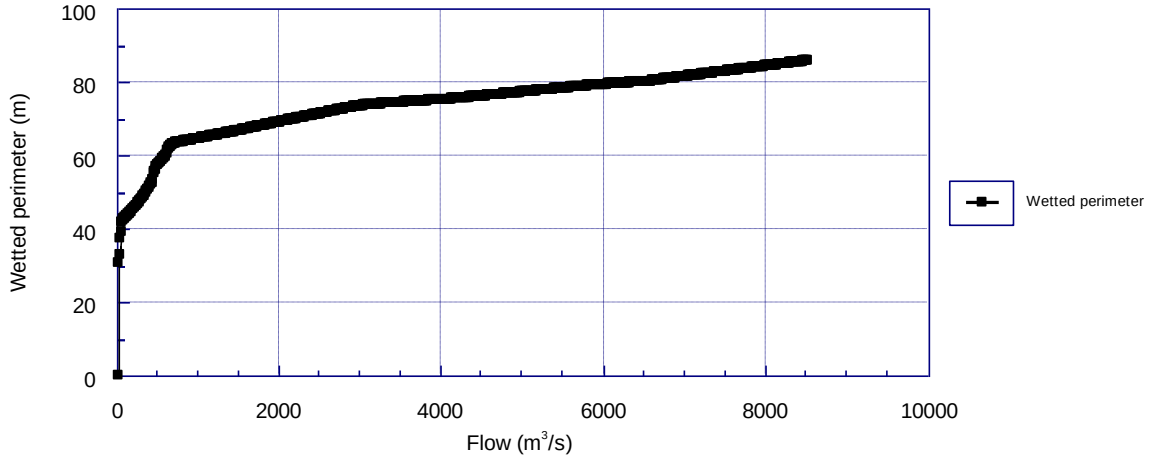


Fig. 4.9: Simulated wetted perimeter for the historical flows at Rudraprayag (before confluence)

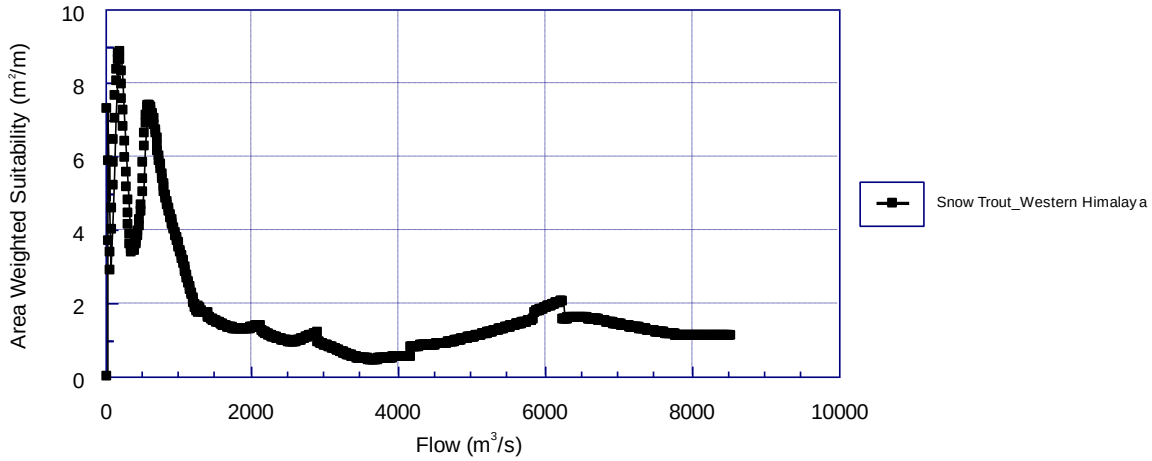


Fig. 4.10: Simulated area weighted suitability for the historical flows at Rudraprayag (before confluence)

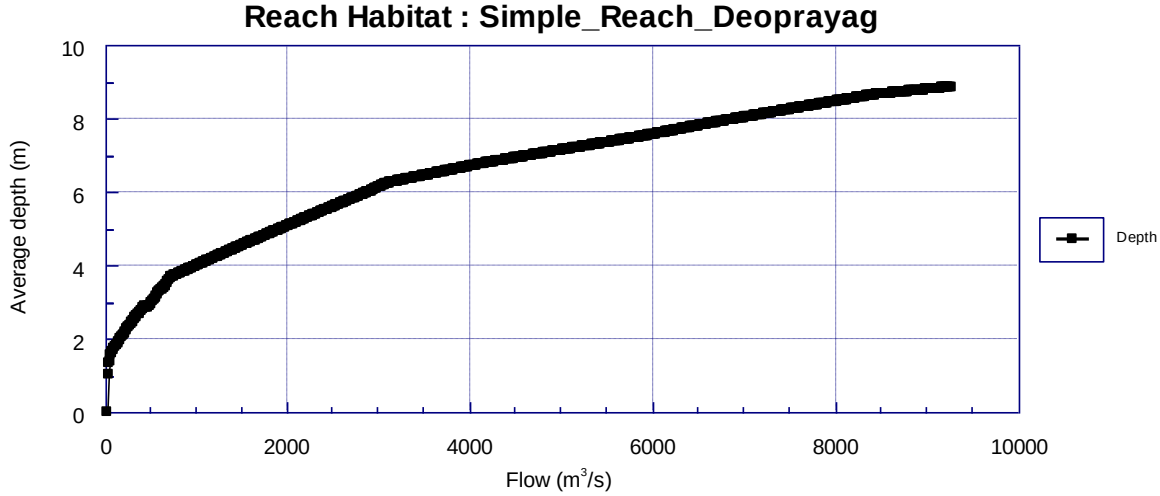


Fig. 4.11: Simulated average water depth for the historical flows at Devprayag (after confluence)

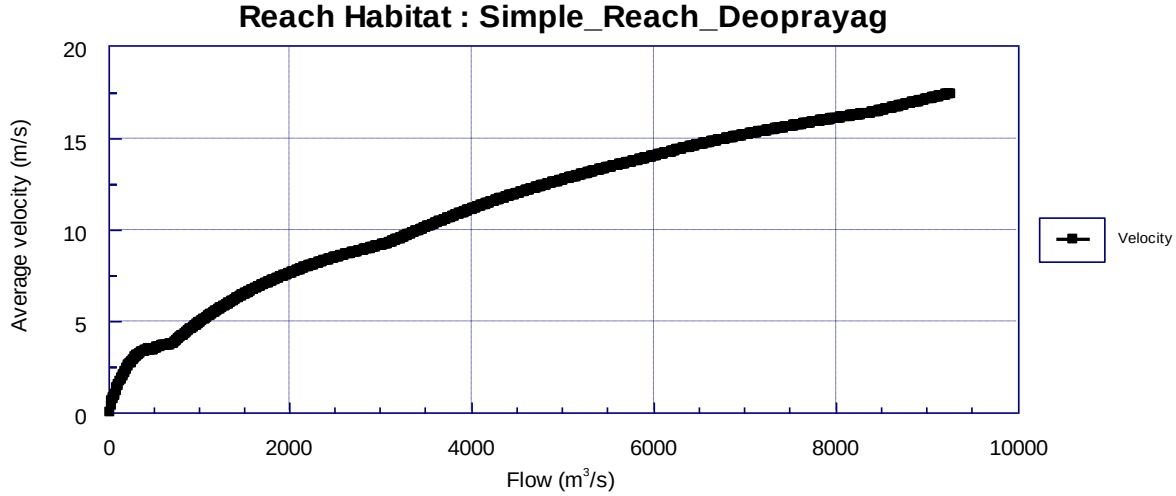


Fig. 4.12: Simulated average water velocity for the historical flows at Devprayag (after confluence)

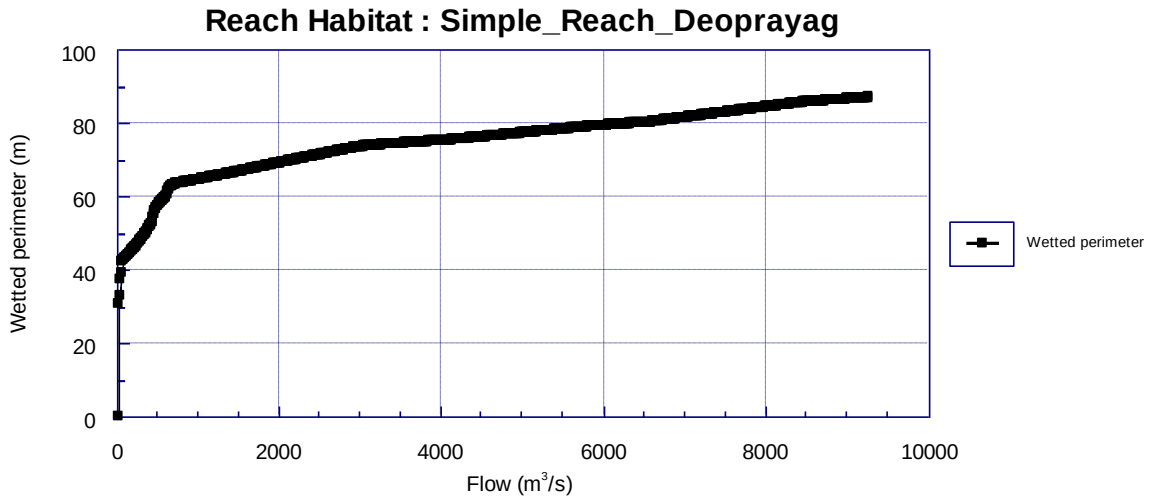


Fig. 4.13: Simulated wetted perimeter for the historical flows at Devprayag (after confluence)

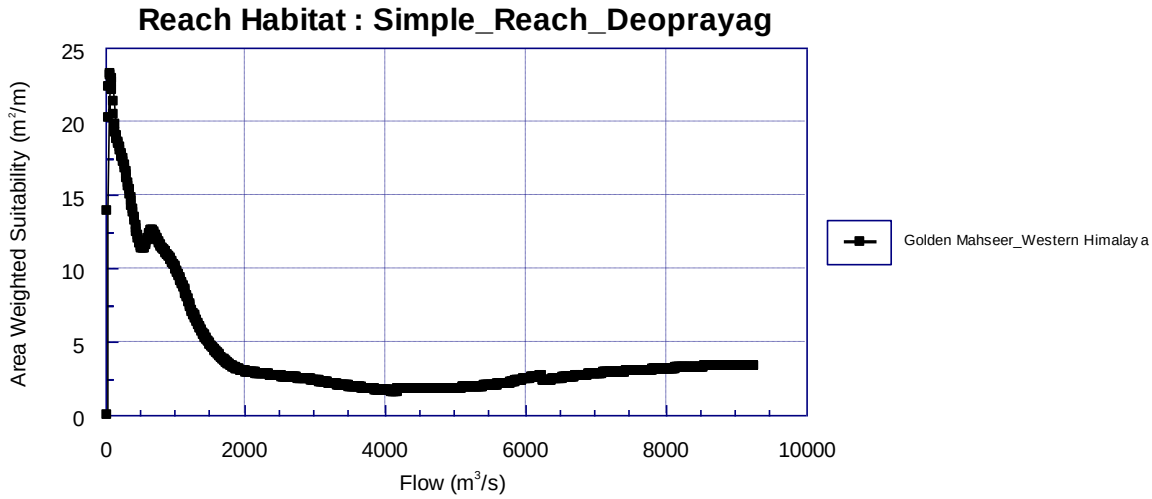


Fig. 4.14: Simulated area weighted suitability for the historical flows at Devprayag (after confluence)

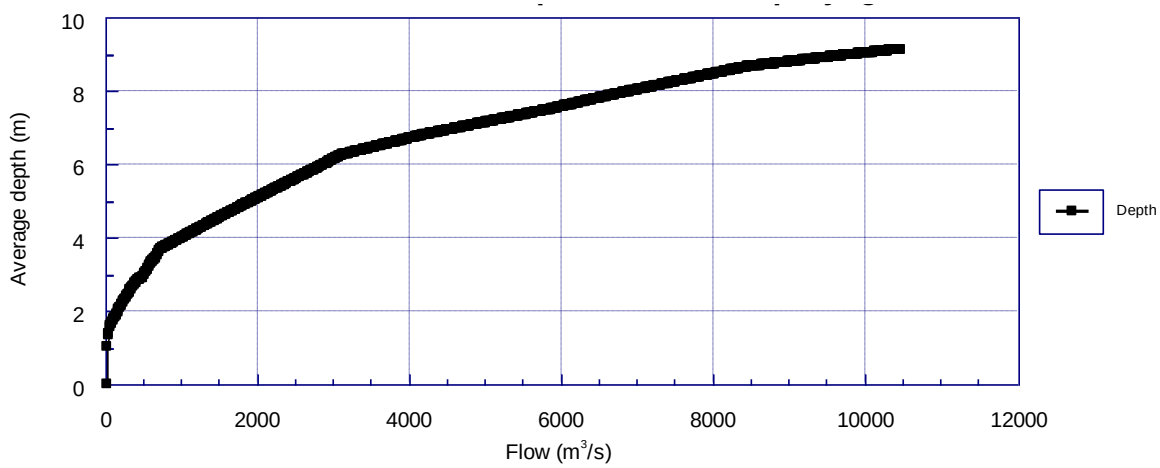


Fig. 4.15: Simulated average water depth for the historical flows at Rishikesh

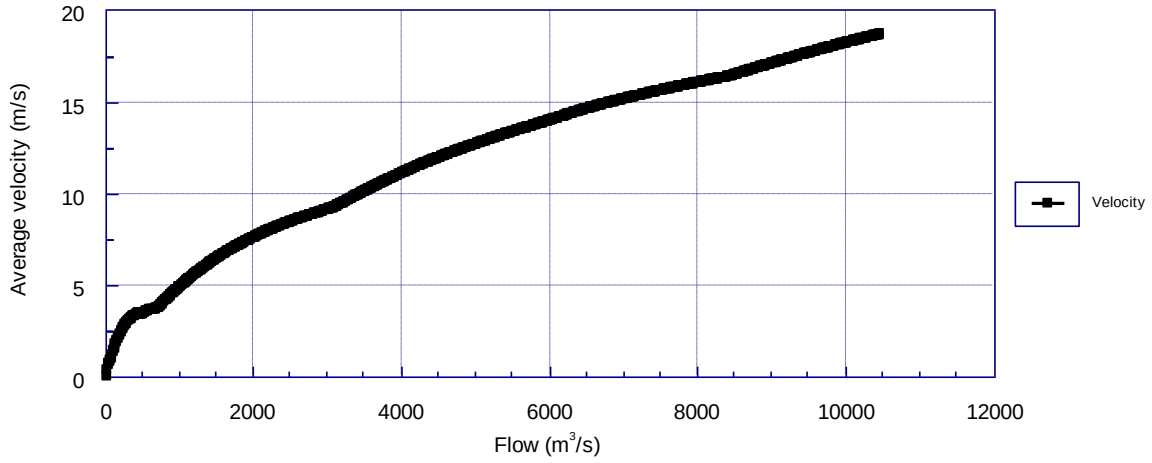


Fig. 4.16: Simulated average water velocity for the historical flows at Rishikesh

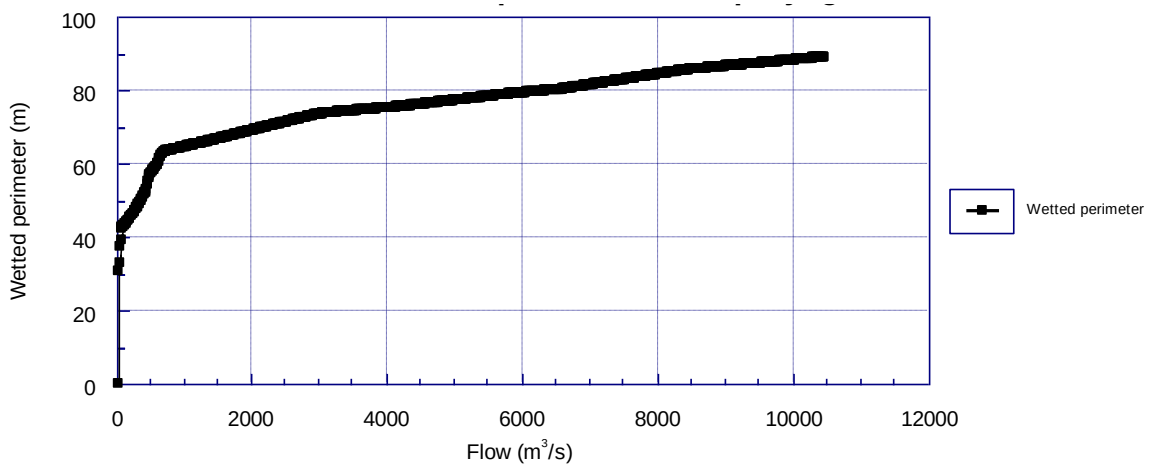


Fig. 4.17: Simulated wetted perimeter for the historical flows at Rishikesh

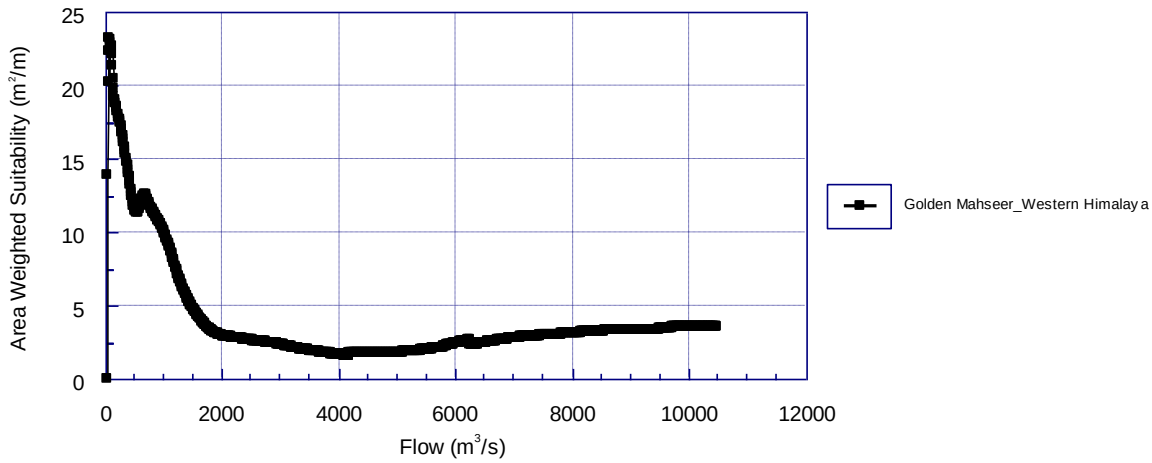


Fig. 4.18: Simulated area weighted suitability for the historical flows at Rishikesh

4.4.2 AWS Duration Analysis for Assessment of Environmental Flows

The SEFA estimates the area weighted suitability for the range of historical flows, cross-section and the input keystone species. The AWS series obtained for the historical flows may further be used for the AWS duration analysis similar like flow duration analysis. This analysis will help in predicting the range of AWS which was available at the historical flows for different frequencies for different periods. In this study this analysis has been carried out on monthly basis and the results are shown in Figs. 4.19 to 4.22 and Tables 4.15 to 4.19.

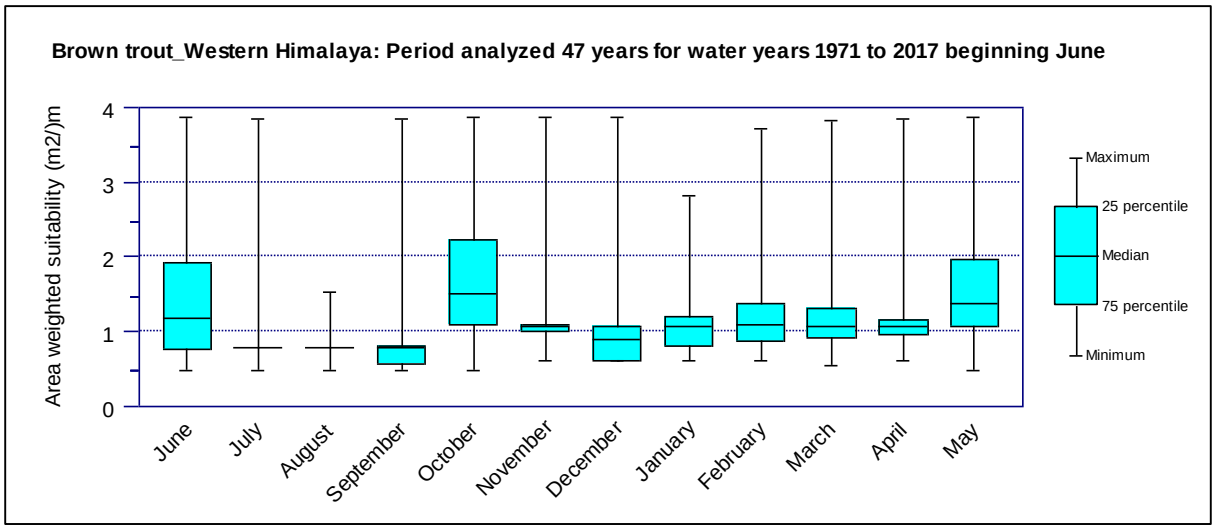


Fig. 4.19: AWS duration analysis for Joshimath for Brown Trout

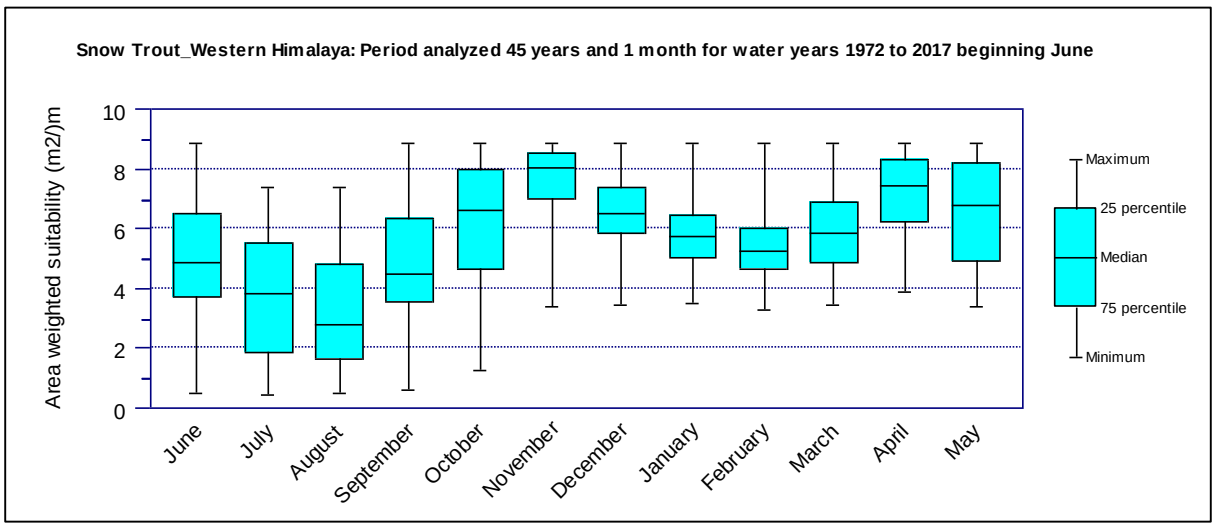


Fig. 4.20: AWS duration analysis for Rudraprayag (before confluence) for Snow Trout

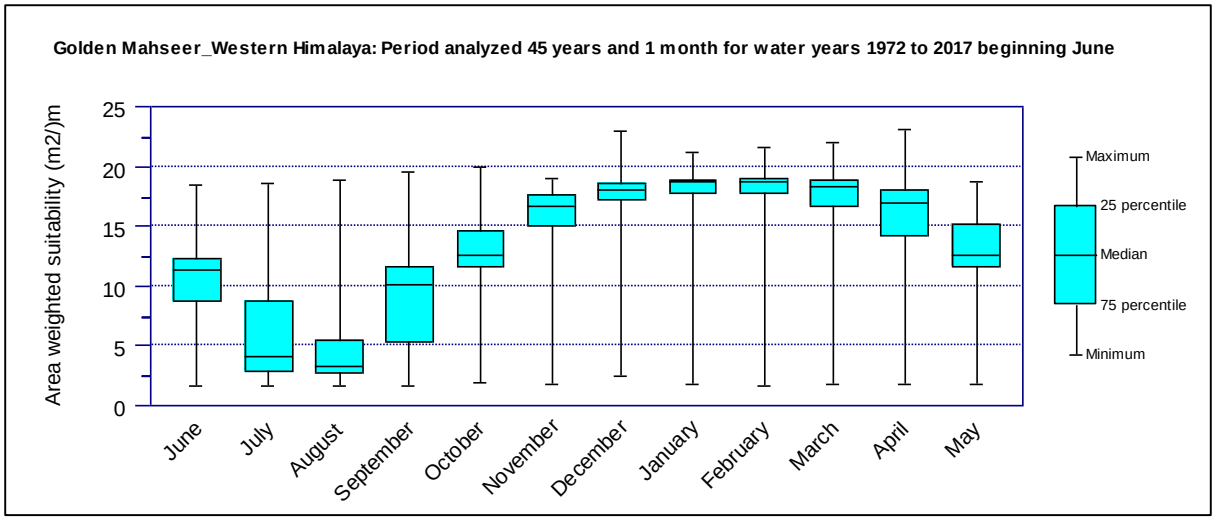


Fig. 4.21: AWS duration analysis for Devprayag (after confluence) for Golden Mahseer

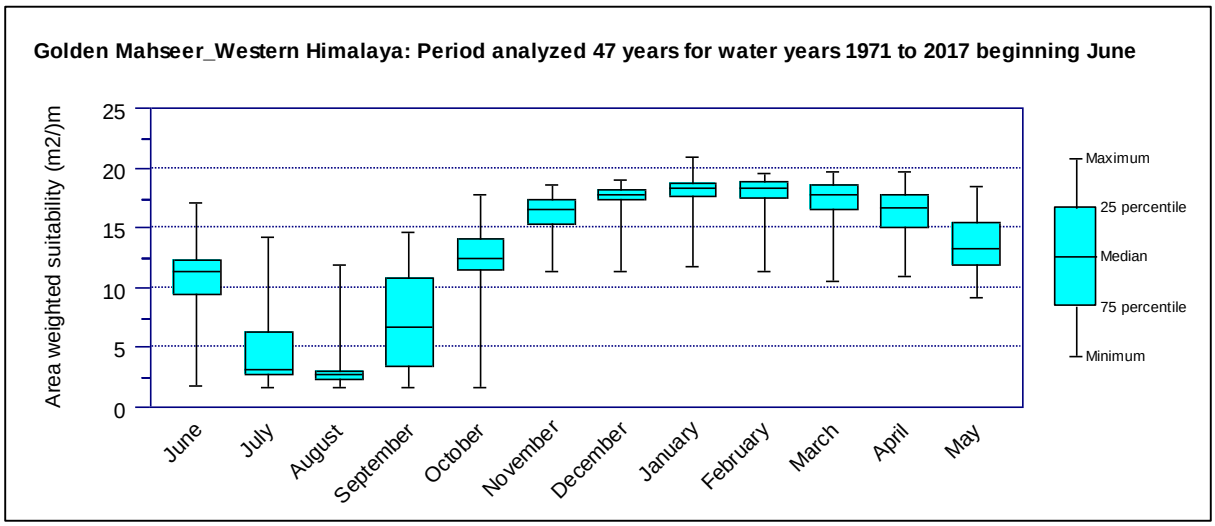


Fig. 4.22: AWS duration analysis for Rishikesh for Golden Mahseer

Table 4.15: Seasonal AWS (in m^2/m of channel) Statics for Joshimath

Season	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Sample size	1410	1457	1457	1410	1457	1410	1457	1457	1328	1457	1410	1457
Minimum	0.477	0.477	0.477	0.477	0.477	0.604	0.604	0.604	0.604	0.539	0.604	0.479
Maximum	3.864	3.857	1.522	3.845	3.863	3.863	3.862	2.816	3.714	3.836	3.85	3.864
Mean	1.427	0.766	0.764	0.88	1.761	1.178	0.895	1.042	1.148	1.137	1.141	1.681
Median	1.188	0.78	0.78	0.78	1.506	1.079	0.905	1.067	1.082	1.077	1.078	1.369
75% exceedence	0.769	0.78	0.78	0.576	1.085	1.015	0.617	0.804	0.877	0.908	0.959	1.08
25% exceedence	1.916	0.78	0.78	0.801	2.221	1.086	1.072	1.204	1.381	1.316	1.158	1.958
Standard deviation (denom. = n-1)	0.922	0.269	0.076	0.496	0.883	0.581	0.302	0.312	0.401	0.426	0.486	0.851

Table 4.16: Seasonal AWS (in m^2/m of channel) Statics for Rudraprayag

Season	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Sample size	1380	1395	1395	1350	1395	1350	1395	1395	1271	1395	1350	1395
Minimum	0.466	0.463	0.479	0.605	1.239	3.378	3.431	3.502	3.303	3.424	3.889	3.376
Maximum	8.846	7.395	7.395	8.843	8.847	8.847	8.845	8.836	8.843	8.847	8.847	8.847
Mean	5.093	3.925	3.353	4.737	6.319	7.63	6.548	5.776	5.393	5.894	7.182	6.485
Median	4.854	3.815	2.77	4.479	6.601	8.021	6.492	5.711	5.253	5.821	7.44	6.772
75% exceedence	3.694	1.872	1.613	3.56	4.637	7.01	5.851	5.036	4.642	4.859	6.208	4.914
25% exceedence	6.495	5.529	4.787	6.365	7.974	8.503	7.399	6.456	6.015	6.86	8.325	8.173
Standard deviation (denom. = n-1)	1.624	2.025	2	1.729	1.821	1.189	1.133	1.072	1.102	1.306	1.303	1.817

Table 4.17: Seasonal AWS (in m^2/m of channel) Statics for Devprayag

Season	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Sample size	1380	1395	1395	1350	1395	1350	1395	1395	1271	1395	1350	1395
Minimum	1.655	1.591	1.576	1.627	1.923	1.798	2.469	1.748	1.692	1.796	1.782	1.78
Maximum	18.511	18.534	18.902	19.498	19.998	19.029	22.89	21.198	21.556	21.972	23.034	18.734
Mean	10.343	5.962	5.141	8.934	12.857	15.714	16.932	17.156	17.331	17.031	15.706	13.109
Median	11.329	4.158	3.219	10.047	12.516	16.651	18.057	18.676	18.777	18.256	16.893	12.57
75% exceedence	8.753	2.91	2.721	5.358	11.552	14.976	17.239	17.754	17.749	16.692	14.201	11.62
25% exceedence	12.266	8.751	5.441	11.62	14.557	17.559	18.62	18.844	18.983	18.822	18.005	15.114
Standard deviation (denom. = n-1)	3.238	3.817	3.888	3.833	2.709	2.983	3.138	3.765	3.479	3.319	3.442	2.912

Table 4.18: Seasonal AWS (in m^2/m of channel) Statics for Rishikesh

Season	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Sample size	1410	1457	1457	1410	1457	1410	1457	1457	1328	1457	1410	1457
Minimum	1.739	1.575	1.575	1.574	1.639	11.302	11.337	11.814	11.304	10.559	10.951	9.159
Maximum	17.144	14.2	11.867	14.622	17.701	18.52	18.961	20.869	19.581	19.718	19.638	18.499
Mean	10.42	4.761	3.097	7.066	12.745	15.997	17.484	17.971	17.939	17.354	16.248	13.719
Median	11.407	3.173	2.688	6.649	12.407	16.488	17.716	18.308	18.373	17.774	16.674	13.206
75% exceedence	9.372	2.675	2.318	3.37	11.52	15.327	17.283	17.579	17.539	16.564	15.062	11.834
25% exceedence	12.297	6.34	3.036	10.781	14.084	17.329	18.167	18.719	18.788	18.623	17.703	15.483
Standard deviation (denom. = n-1)	3.213	3.026	1.634	3.651	1.952	1.746	1.117	1.047	1.307	1.683	1.91	2.105

It has been assumed here that the environmental flows may be kept for maintaining the the median or higher values of AWS for sustenance of keystone aquatic species. The median values of AWS at these sites and corresponding flows for maintaining median or higher AWS have been summarized in the Tables 4.19 to 4.22. In these tables, the recommended values as environmental flows have also been shown as percentages of long-term average flows during respective months. From the tables, it is indicated that the recommended e-flows are falling in the range from 26.32 to 41.81 % of average monthly flows at Joshimath site, from 20.94 to 38.64% of average monthly flows at Rudraprayag site, from 23.67 to 33.81% of average monthly flows at Devprayag site (after confluence) and from 24.66 to 37.17% of average monthly flows at Rishikesh site.

Table 4.19: Recommended values of environmental flows for the sustenance of aquatic species at Joshimath

Season	Average Flows	Median AWS	Corresponding Min. Q with median/higher AWS in the season	% of av flow
Jun	311.969	1.188	90	28.85
Jul	454.979	0.78	140	30.77
Aug	417.261	0.78	140	33.55
Sep	254.686	0.78	100	39.26
Oct	124.398	1.506	40	32.15
Nov	73.359	1.079	30	40.89
Dec	47.834	0.905	20	41.81
Jan	34.524	1.067	10	28.97
Feb	32.500	1.082	10	30.77
Mar	36.613	1.077	10	27.31
Apr	61.248	1.078	20	32.65
May	151.976	1.369	40	26.32

Table 4.20: Recommended values of environmental flows for the sustenance of aquatic species at Rudraprayag (before confluence)

Season	Average Flows	Median AWS	Corresponding Min. Q with median/higher AWS in the season	% of av. flow
Jun	515.181	4.854	170	33.00
Jul	1026.306	3.815	310	30.21
Aug	1151.970	2.77	340	29.51
Sep	687.333	4.479	160	23.28
Oct	286.543	6.601	60	20.94
Nov	167.385	8.021	40	23.90
Dec	110.415	6.492	30	27.17
Jan	90.837	5.711	20	22.02
Feb	83.242	5.253	20	24.03
Mar	92.745	5.821	30	32.35
Apr	129.404	7.44	50	38.64
May	246.074	6.772	80	32.51

Table 4.21: Recommended values of environmental flows for the sustenance of aquatic species at Devprayag (after confluence)

Season	Average Flows	Median AWS	Corresponding Min. Q with median/higher AWS in the season	% of av flow
Jun	853.7192	11.329	280	32.80
Jul	1705.767	4.158	510	29.90
Aug	2040.756	3.219	690	33.81
Sep	1181.971	10.047	310	26.23
Oct	477.6988	12.516	120	25.12
Nov	286.7606	16.651	80	27.90
Dec	216.6683	18.057	60	27.69
Jan	211.2374	18.676	50	23.67
Feb	202.3438	18.777	50	24.71
Mar	230.8628	18.256	60	25.90
Apr	280.5498	16.893	80	28.51
May	454.9971	12.57	120	26.37

Table 4.22: Recommended values of environmental flows for the sustenance of aquatic species at Rishikesh

Season	Average Flows	Median AWS	Corresponding Min. Q with median/higher AWS in the season	% of av flow
Jun	860.8928	11.407	320	37.17
Jul	1950.167	3.173	630	32.30
Aug	2545.792	2.688	740	29.07
Sep	1459.736	6.649	360	24.66
Oct	509.9524	12.407	180	35.30
Nov	290.5637	16.488	100	34.42
Dec	217.7772	17.716	80	36.74
Jan	191.3961	18.308	60	31.35
Feb	191.5126	18.373	60	31.33
Mar	221.4268	17.774	80	36.13
Apr	277.8099	16.674	90	32.40
May	425.6624	13.206	150	35.23

CHAPTER – 5
CONCLUSIONS

Western Himalayan region is the main stay of the Himalayan water tower holding more than 90% of glacier and cryospheric resources in India and abundant monsoon rainfall along its foothills. Major rivers of the region; Ganga, Yamuna, Sutlej, Beas, Chenab, Jhelum, Zanskar, Indus, Shyok and Nubra all originate from the mighty Himalayas and contribute immensely to the development of our country and our neighbouring countries.

All the rivers of this region have huge hydropower potential. A number of hydropower schemes on these rivers are in different stages of planning, construction and operation. In most of these schemes, river water is diverted for power generation and returned to the river at a downstream location altering the flow regime of the river in specific reaches. Even if the individual schemes may not be significantly detrimental to the physical and biotic environment, the combined effect of these schemes could be significant. The problem may be more complex as the climate change and the land use changes are also affecting the hydrologic regime of these rivers.

A number of attempts for assessing E-Flows in this region have been made during last 15 years (Jain and Kumar, 2014). But, these efforts have been mostly based on hydrological or hydraulic approaches with application of limited habitat preferences. These studies are limited by the fact that neither the data on abundance of aquatic species is available nor there is any developed hydrology-ecology relationships. In this connection, the present study has been carried out to develop habitat suitability curves for the aquatic species of western Himalayan streams using the available literature and to use these curves for the assessment of environmental flows using habitat simulation modelling.

In the present study, the data/information on biotic parameters (abundance of aquatic species) and influencing abiotic parameters (water depth & velocity and water quality parameters: water temperature, pH, DO, BOD, turbidity etc.) for the concurrent period have been compiled for 48 sites in the western Himalayan region. It was found from the literature that the keystone species for upper (>1500m), middle (500-1500m) and lower (< 500m) zones are Brown Trout, Snow Trout and Golden Mahseer respectively. Hence, the habitat suitability curves for these species have been developed through the specific module in the 'System for Environmental Flow Analysis (SEFA)' software utilizing the data/information available in the compiled literature.

For habitat simulation modelling four sites have been selected viz. Joshimath (upper zone), Rudraprayag (middle zone) and Devprayag & Rishikesh (lower zone). Further, the developed habitat suitability curves alongwith discharge and cross-section data at these four sites have been used for the simulations through habitat simulation modelling exercise. The final modelling output is the Area Weighted Suitability (m^2/m of reach length) which indicates

the suitability of a particular discharge for the habitat sustenance. Further, AWS Duration analysis was also performed on monthly basis at these sites for the keystone species which provides the median, 90%, 75%, 25%, 10% and mean of AWS for the historical flow series.

It has been assumed here that the environmental flows may be kept for maintaining the the median or higher values of AWS for sustenance of keystone aquatic species.

The following conclusions may be drawn from the study:

1. The keystone species for upper (>1500m), middle (500-1500m) and lower (< 500m) zones are Brown Trout, Snow Trout and Golden Mahseer respectively.

2. The habitat suitability curves for the keystone species were developed (shown as Fig. 4.2) which may be used for the habitat simulation modelling with more detailed data.

3. Habitat Simulation Modelling provides a number of optional scenarios for the maintenance of different levels of habitat sustenance whereas in case of hydrodynamic modelling, the flows optimum for maintaining a certain depth of water are recommended.

4. The final modelling output of the habitat simulation modelling is the Area Weighted Suitability (m^2/m of reach length) which indicates the suitability of a particular discharge for the habitat sustenance. Based on the variability of AWS for the historical flow variability, AWS duration analysis may be carried out in the SEFA software which may further be used for selecting a particular level of AWS for providing reasonable habitat for different seasons.

5. Assuming that the environmental flows may be kept for maintaining the median or higher values of AWS for sustenance of keystone aquatic species, it was found that the recommended e-flows are falling in the range from 26.32 to 41.81 % of average monthly flows at Joshimath site, from 20.94 to 38.64% of average monthly flows at Rudraprayag site, from 23.67 to 33.81% of average monthly flows at Devprayag site (after confluence) and from 24.66 to 37.17% of average monthly flows at Rishikesh site.

FUTURE SCOPE OF WORK

The response of species to variety of flow conditions is very complex phenomenon which is dependent on a number of factors including depth, velocity, temperature and other water quality parameters. The representation of habitat only in terms of depth, velocity and substrate as being carried out in habitat simulation modelling approach is just the simplification of this complex phenomenon.

The habitat suitability varies significantly with respect to the species and location. The curves developed for this habitat simulation modelling exercise are based on the secondary

literature available. The results may be different if we derive the site-specific habitat suitability curves for the same keystone species.

The SEFA software also has provisions for temperature modelling, DO modelling, flow requirement for sediment flushing and inundation analysis. Due to non-availability of data for the present study, these may be attempted.

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