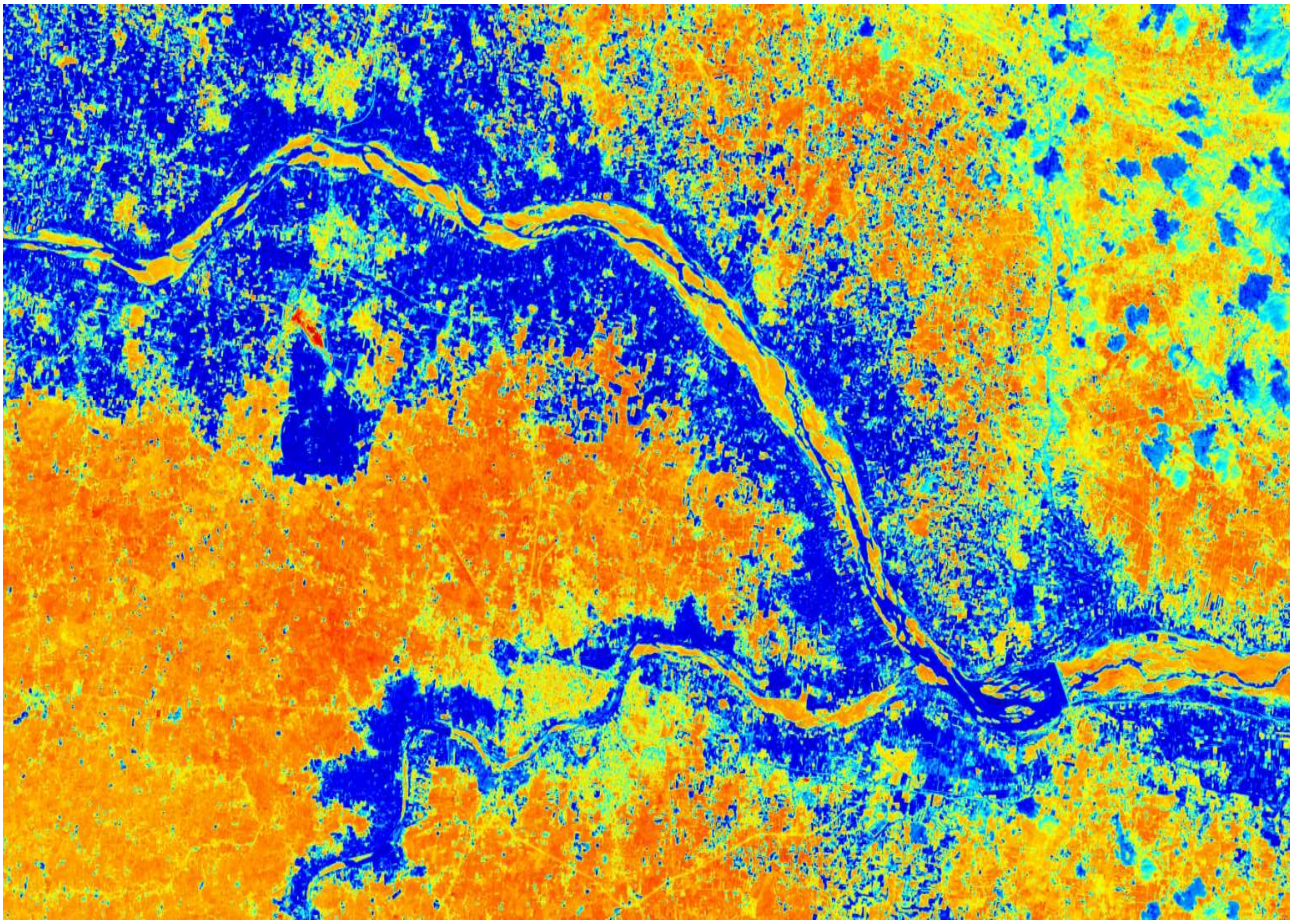
Parched Kaveri

A preliminary assessment of flow alteration and ecological condition of sub-basins of Kaveri river using global datasets



Surabhi Singh [4752325] | M.Sc. Environmental Engineering | TU Delft 2018-19

M.Sc. Thesis in Environmental Engineering
Graduation Report
Parched Kaveri : A preliminary assessment of flow alteration and ecological condition of sub-basins of Kaveri river using global datasets

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October,2019

Cover: Sentinel 2B L1C Imagery with Moisture Index Renderer (Date : 18-02-2019)

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Graduation Report

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Source : (1),(2),(3) - Kaveri river and its tributaries running dry (Source : ESRI Digital Globe Imagery)
(4) Sand Mining in Kaveri River (Credit - Ashvij Putta)

*“ Every species has a role to play in the tapestry of life and
if we do not protect this biodiversity, if we continue over-consuming and
wasting natural resources, the tapestry will gradually fall apart.”*

Jane Goodall


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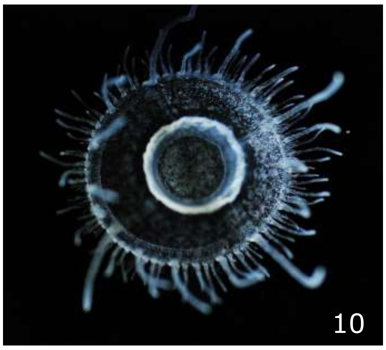
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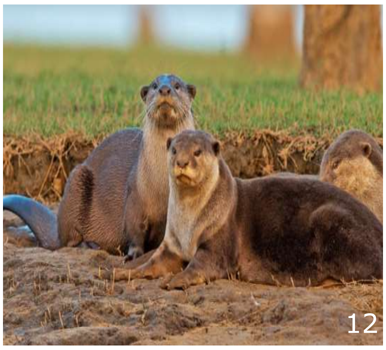
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Images : (L-R) Freshwater Crabs : 1. Gubernatoriana waghi (Credit: Rachit Shah) 2. Ghatiana atropurpurea (Credit: Arjun Kamdar)
3. Gubernatoriana thackerayi (Credit: Shailesh Bhosale)
Odonata : 4. Aciagrion Hisopa 5. Euphea Dispar 6. Calocypha Laidlawi (Source: Indian Foundation for Butterflies, https://www.indianodonata.org/)
Fish : 7. Mahaseer -Tor Musullah 8.Tenualosa Ilisha (Source : https://www.fishbase.in)
9. Mahaseer -Tor Khudree (Credit: Steve Lockett, Mahaseer Trust)
Others: 10. Freshwater Jellyfish - Craspedacusta sowerbi (Credit: Amoghavarsha) 11. Molluscs - Lamellidens (Source: https://www.conchology.be/)
12. Otters (Credit: Nisarg Prakash)

ABSTRACT

Freshwater biodiversity is in a state of crisis with an annual decline rate of 3.9% compared to 1.1% decline in terrestrial biodiversity (Living Planet Index). The actual decline rate may be higher than estimated as many of the species are data deficient or not yet assessed or became extinct before assessment. We have far surpassed the sustainable or natural limit of reductions in populations of freshwater species. With an unprecedented increase in global energy and water demand, planetaries boundaries for sustainable use of freshwater may be overstepped in the near future, as presently visible at a local scale. A staggering decline in freshwater biodiversity is a first warning signal of a looming global water crisis. With continued pressures like river fragmentation, flow regulation, overextraction of surface or groundwater, pollution, invasive species and climate change, on freshwater habitats, this crisis may shift one level higher and impact human species severely.

Environmental flows forms the link between ecological health of a river and the ecosystem services we derive from it. It can be a great tool to achieve twin objective of maintaining the ecosystem integrity of freshwater habitats and deciding trade-offs for ensuring sustainable water management in a river basin. This study focuses on developing a holistic methodology for preliminary assessment of ecosystem integrity or ecological health of a river basin, which can be easily adapted to other river basins using open source global datasets. The proposed methodology was applied to Kaveri basin to test its applicability and identify the limitations of available global datasets. A widely accepted regional environmental flow assessment framework, ELOHA (Ecological Limits of Hydrological Alteration) was adapted by using global datasets. A global river classification dataset was used to identify the river classes in Kaveri basin. Monthly hydrological alteration in magnitude at the location of gauge stations was calculated, using PCR-GLOBWB data as reference for natural flow conditions, in absence of records for natural flow in a highly modified Kaveri basin. An ecosystem integrity indicator framework was developed to assess the hydrologic, geomorphic and ecological modifications in the river basin. Indicators grouped under four main categories - Connectivity status, Land Use, Biodiversity, Water Quality were adopted using exiting global datasets and values for all the sub-basins of Kaver basin were estimated.

Finally an attempt to derive flow alteration-ecological response was made. Threatened fish species percentage, quantified using IUCN spatial dataset, showed an increase in value with increase in alteration in flow magnitude. No clear reationship was observed when data for other taxonomic groups like plants, molluscs, odonata, shrimps and crabs were used. Hence, species of concern (IUCN red list category - CR, EN,VU) data can be useful in deriving preliminary flow alteration-ecological response relationship. An attempt to find linkage between flow alteration and floodplain gross primary productivity was also made. In dry season an inverse relationship was observed at few gauge stations but in general other climatic factors like rainfall and evapotranspiration had greater influence on gross primary productivity. Impact on gross primary productivity due to flow alteration could not be isolated using existing datasets because of coarse resolution.

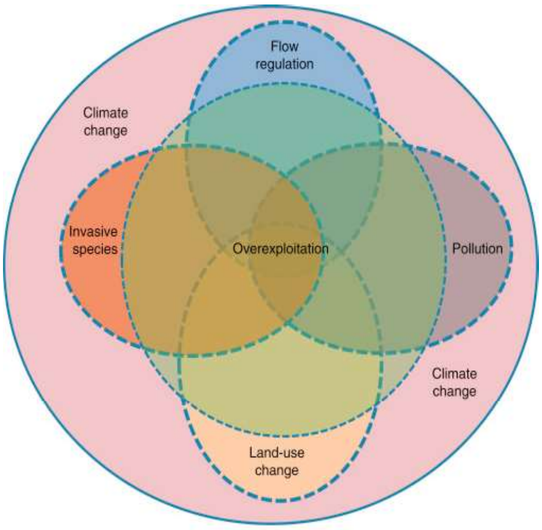

Fig . Global threats to freshwater habitats
(Source: Dudgeon, D. (2019))

KEYWORDS : Environmental Flow (E-Flow) , Biodiversity, Ecosystem Integrity, Flow Alterations, Species Richness, Flow Alteration-Ecological Response Relationships, Connectivity, Land Cover Naturalness, Biodiversity

ACKNOWLEDGEMENT

I got introduced to the concept of Environmental Flows through Prof. G D Agarwal, who passed away last year while he was on a 111 days long fast demanding environmental flows for river Ganga. His commitment and love for river Ganga inspired me to dig deeper into this topic. I became more curious about how environmental flows are determined and monitored. In India till date there is no river for which environmental flow assessments have been completed for the entire stretch while the anthropogenic pressures on the rivers are increasing at an alarming rate. Though I could not achieve what I had ambitiously decided at the start of my thesis, I have learnt a lot in the process.

I am thankful to Prof. Wim Bastianssen who gave me this project and gave me a direction in the beginning of the project. Prof. Michael Mcclain has given me constant support throughout this project. He has been an inspiration for me, for diving in to this topic and staying updated with all the new developments in the environmental flow community. His enthusiasm for environmental flows is very infectious. I am also thankful to Claire Michailovsky, my daily supervisor, who gave her valuable insigths, helped me in times of crisis and pushed me to produce results. Markus Hrachowitz also gave me valuable insights during the course of this project.

I came across many people who enriched me with their experience and knowledge. Thank you Nisarg Prakash, Steve Lockett and Sergio for taking out time for me. A special mention goes to Anjana Ekka who has been a constant support to me in all aspects. Thank you for sharing all the data with me and being there with me through all the ups and downs.

I am very greatful to have the love and support of my friends Pooja, Taveshi, Saket, Kalrav, Bhavya, Moulik, Soham even when I had gone into a shell. I am very indebted to my therapist Natasja who helped me recover from PTSD, instilled confidence in me and gave me a new perspective. Thank you for patiently hearing to me and solving all my querries. I would also like to thank my parents and my partner Harsha for inspiring me and being there for me. I struggled to maintain a balance between my emotions and my work. I regret that I couldn't give my best to this project but I am determined to pursue further in this field. I am happy that I could figure out my calling through this Master thesis.

I hope this report sparks the reader's enthusiasm and interest in environmental flows.

Surabhi Singh
Delft, October 2019

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5 RESULTS & DISCUSSION

Hump-Backed Mahaseer in Coorg, Karnataka, India
Credit : Bopanna Pattada

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ABBREVATIONS

SDG	Sustainable Development Goals
E-Flow	Environmental Flow
EMC	Environment Management Class
IWMI	International Water Management Institute
IUCN	International Union for Conservation of Nature
CR	Critically Endangered
VU	Vulnerable
EN	Endangered
ELOHA	Ecological Limits of Hydrological Alterations
GEOBON	Group On Earth Observations Biodiversity Observation Network
WWF	World Wildlife Fund
LPI	Living Planet Index

1 INTRODUCTION

1.1. Research Motivation

Globally freshwater ecosystem occupy 1% of earth's surface but support a disproportionately high biodiversity and provide a wide range of ecosystem services like flood regulation; food and freshwater supply; recycling of nutrients, water; recharge of groundwater; transport of sediments and recreational opportunities to human beings. A WWF report states that freshwater, including rivers, lakes and wetlands, are the most threatened of all global habitats. Globally freshwater species populations have dropped by 83% on average ,i.e., 4% a year, since 1970 according to Living Planet Index report (Living planet report, 2018).

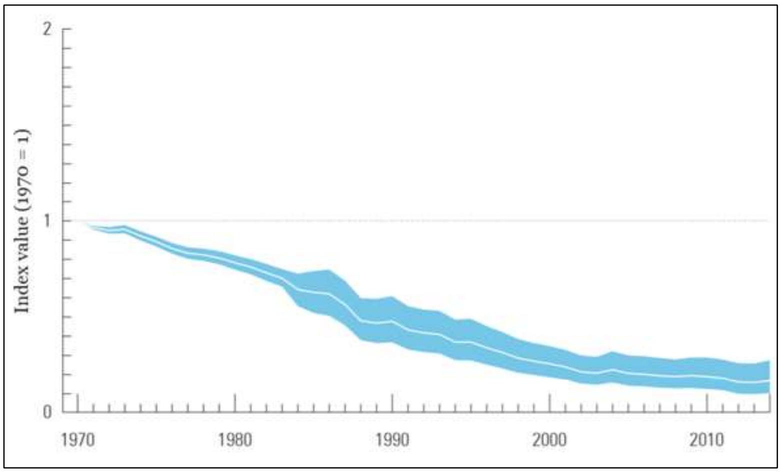


Fig 1.1. Freshwater Living Planet Index (LPI) showing a decline of 83% (Range -73% to -90%) in freshwater populations. (Source: (Living planet report, 2018))

Free flowing rivers connect the terrestrial and marine ecosystems and provide vital ecosystem services. Rivers exchange water, nutrients, sediments, organisms and energy, while flowing through the riverine ecosystems - river channels, floodplains, riparian zones, lakes and wetlands. Increasing global water and energy demand has introduced many pressures on riverine ecosystems. It is widely known by the scientific community that riverine ecosystems are facing threats due to anthropogenic activities like dam constructions, illegal sand mining, habitat degradation,flow regulation, pollution and overexploitation. Reservoirs store around 10,000 km^3 of water (five times the standing volume of rivers), reducing the sediment flux to oceans by 25%. A recent study found out that 48.2% of river reaches are impacted by diminished river connectivity while only 37% of rivers (length greater than1000 km) remain free flowing. River fragmentation (longitudnal connectivity) by construction of dams and water diversion structures is one of the dominant pressure factor affecting rivers worldwide. Climate change will further increase the pressures on the rivers through alterations in flow patterns and intermittency, modifications in the frequency, magnitude and timing of droughts or floods, and changes to water quality and ecological communities (Grill et al., 2019). There is an urgent need to conserve freshwater resources and restore the rivers to their natural state by allocating water for the environment.

1.2. Problem Statement and Knowledge Gaps

Hydrological human disturbance can be grouped under four categories :
a) Alteration in land surface water balance (climate change, change in land use and land cover)
b) Artificial impoundment and diversion of surface water (dams for irrigation, water supply, flood control and hydroelectric power.)
c) Withdrawal of groundwater (for domestic, irrigation or industrial uses)
d) Modification of natural surface drainage system (channelization and wetland drainage)

A complex interplay of factors mentioned above, modifies the natural flow regime of rivers. Due to lack of sufficient data and increasing uncertainty it is difficult to quantify these impacts, individually. A number of indices have been developed by scientists to assess the hydrological alteration in flow regime using streamflow data. Using flow data from undisturbed time-period, natural patterns in flow components can be assessed. Flow alteration indices can be computed at daily or monthly scale, by quantifying the departure from nature flow regime, in respective flow components. Biophysical processes linked to natural flow patterns gives an idea about plausible ecological responses to flow alteration.

In order to restore the ecological integrity of riverine ecosystems, the concept of environmental flows was introduced to reserve water for the environment. Environmental flows describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being. In this definition, aquatic ecosystems include rivers, streams, springs, riparian, floodplain and other wetlands, lakes, coastal water bodies, including lagoons and estuaries, and groundwater-dependent ecosystems (Arthington et al., 2018). Since the 1940s more than 200 methods have been developed for environmental flow assessment (Tharme, 2003). Recently environmental flow was incorporated in calculation of water stress indicator (SDG : 6.4.2) in order to assess the availability of excess which can be utilized for economic purposes.

Global Environmental Flow information system developed by IWMI (International Water Management Institute) provides data for environmental flow requirements for all the river basins as a long time average, which can be used for SDG reporting till 2030 (Dickens, Smakhtin, Biancalani, Villholth, & Eriyagama, 2019). There is no explicit linkage between environmental flow requirement and biodiversity threat index used for defining environment management class (EMC). EMC is defined as“the ecological condition of a river in terms of the deviation in biophysical components from natural reference conditions that will result from implementation of particular management objective” (Dickens, Smakhtin, Biancalani, Villholth, & Eriyagama, 2019). EMCs is grouped into 5 discrete categories from A (natural) to E (seriously modified) and are quantified using Biodiversity Threat Index (Vörösmarty et al., 2010). Vorosmarty utilized raster datasets of different drivers grouped under four categories to compute this index at a spatial resolution of 0.5 degree. Only two categories of drivers, which are listed below, were considered for calculation of environmental flow requirement.

1. Water Resource Development (Dam Density, River Fragmentation, Consumptive water loss, Human water stress, Agriculture water stress, Flow disruption)

2. Biotic Factors (Non-Native Fish, Fishing pressure, Aquaculture pressure)

Flow duration curves based on natural flow time series from a global hydrological model were shifted stepwise with respect to EMC based on a thumb rule (Dickens, Smakhtin, Biancalani, Villholth, & Eriyagama, 2019).The global datasets used for computation of these drivers are static datasets and are not periodically updated hence it doesn't capture the dynamic behavior of riverine ecosystems. Also, seasonality of flow regime and the related ecological responses have not been captured in this method.

Environmental flow assessments are expensive and require a team of multidisciplinary experts for assessing impact of flow alteration on ecology. Many countries lack sufficient data and resources to carry out such expensive assessments. The rate at which freshwater habitats are getting degraded it is necessary to prioritize such assessments by identifying critical locations using freely available global datasets. There is also a need to build an open-access repository of data collected previously. A disconnect between global platforms, (like IUCN- International Union of Conservation of Nature, GEOBON - Group On Earth Observations Biodiversity Observation Network etc.), assessing freshwater biodiversity periodically and environmental flow community is also observed. This gap has to be filled and a flow of information from regional to global level should be established in order to restore ecological balance of riverine ecosystems across the world.

1.3 Research Objectives and Scope

The overall aim of this project is to quantify hydrological alterations and flow-ecology relationships for large river basins.The developed methodology will be global in scope and local in scale which can be easily replicated for other river basins with limited data. Based on the literature review, research questions were formulated as an extension to the studies already conducted by previous authors. The main research question is :

“ How global datasets can be used to understand linkages between river flow and ecosystem health in order to assess and monitor environmental flow requirements of a river basin ? ”

The sub questions which will be answered during the course of this project are listed below.

1. Which global datasets (from macro-scale models or remote sensing) can be used to determine Ecosystem Integrity of a river basin ?
    a. Which indicators can be chosen and grouped under biotic and abiotic components, to determine the ecosystem integrity of a river basin ?
    b. What are the limitations in using remotely sensed data and other global datasets and how can they be improved ?

2. How alterations in flow regime in a river basin can be measured at monthly timescale ?
    a. Which indicators can be used to quantify flow-regime alteration at monthly scale ?
    b. Which datasets can be adopted as a proxy for natural flow regime in a highly modified basin ?

3. What flow-ecology linkages can be determined for a river basin using global datasets ?
    a. What is the effect of flow regime alteration on the species richness of freshwater biodiversity in a river basin ?
    b. Is there any relation between “ecological metabolism” or primary productivity of floodplain and flow alterations ? And what is the impact of other climatic factors like temperature and precipitation on primary productivity of floodplains ?

1.4 Outline of Thesis

The main content of the thesis is organized in six sections. In Section 2, a litreature review of key concepts related to eco-hydrology, natural flow paradigm, ecosystem integrity, flow alteration-ecological relationships have been described. A comparison of existing environmental flow assessments at global scale is presented to highlight the research gaps. The subsequent section is a description of study area, Kaveri river basin. A brief description about river network, climate & geography, land use, agricultural practices and reservoirs is included in Section 3. Methodology of this research and datasets used are described in Section 4, followed by a discussion of results obtained alongwith limitations of the study is included in Section 5. Finally, conclusions and recommendations, drawn from the study have been discussed in Section 6.

2 THEORY

This chapter aims to provide theoretical background of the study. It begins with explanation about some key concepts like natural flow paradigm, ecosystem inetgrity and then dwells into sources of flow alteration. In subsequent section plausible ecological responses to flow alteration have been discussed. In Section 2.4 environmental flow assessment methods have been discussed alongwith a review of existing global methodologies for e-flow assessment in order to higlight the research gaps. In the last section role of environmental flows in sustainbale river basin management has been briefly discussed.

2.1 Natural Flow Regime

River flow governs the dynamics of riverine ecosystems and organizes physical habitats and associated biotic communities (Zeiringer, Seliger, Greimel, & Schmutz, 2018). Natural flow regime is largely determined by factors like topography, climate, geology and land cover. Flow variability is a characteristic feature of a river system and is essential for its ecological functioning. Natural flow paradigm by Poff (1977) states that magnitude, frequency, duration, timing and rate of change are the five critical components of flow regime that regulate ecological processes in the riverine ecosystem. Magnitude is the streamflow discharge or amount of water flowing through fixed location per unit time. Frequency refers to how often high flow or low flow conditions occur in a river basin, while duration is the time associated with a certain flow condition. Timing is the measure of regularity or predictability of certain flow events and rate of change or flashiness determines the transition of flow from one magnitude to another. (Poff et al., 1997) Flow regime with all its flow components and natural variability plays a key role in maintaing the ecosystem integrity of riverine ecosystems.

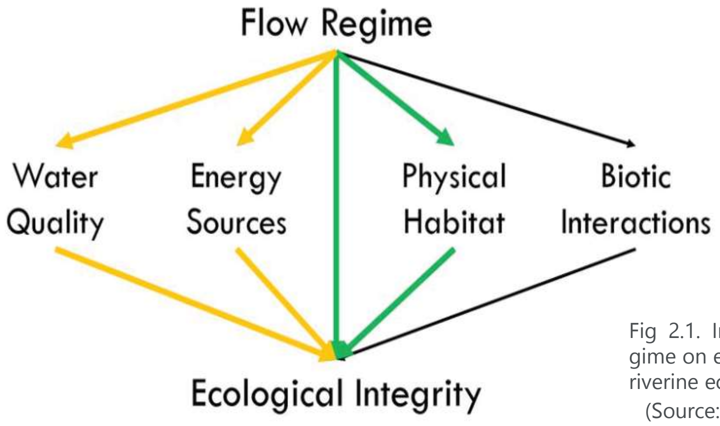


Fig 2.1. Influence of flow regime on ecological integrity of riverine ecosystems
(Source: Poff et al., 1997))

Ecosystem Integrity or Ecological Integrity is the measure of combined role of abiotic (physical-chemical integrity) and biotic (biological integrity) factors that maintains self-sustaining ecosystems. Physical integrity refers to the interatcion of abiotic factors (like water, sediment, vegetation,) that shapes the physical structure and function of a river while biological integrity refers to biotic factors (biological or chemical) that sustains the natural flora and fauna for a riverine ecosystem. The ecosystem integrity, river health, resilience and productivity of riverine ecosystems depends upon the natural variability of flow regime, as well as longitudnal, lateral, temporal and vertical connectivity among them.

2.2 Sources of Flow Alteration

Natural flow variability results from changing precipitation and evapotranspiration patterns associated with impact of land use, climate, etc. on land surface water balance. Increasingly, this naturally flow variability to which aquatic species are accustomed to, is getting disrupted by anthropogenic sources of flow alteration. A summary of human disturbances causing flow alteration in rivers and accompanying hydrologic and geomorphic responses is presented in Table 1. Dams alter the seasonal variations in flow magnitude, immerse large amount of natural vegetation, converting lotic ecosystems into lentic. This result in increased evaporation from water stored in reservoirs and alongwith release of greenhouse emissions due to submerged vegetations. Run-of-the river hydropower projects though involve minimal storages, can impact the low flow conditions and also affect the flow of sediments downstream. Sediments are trapped inside reservoirs reducing flow of sediments downstream, which makes the river bed coarser and causes erosion of river channel when flow is released from dams. Urbanization can lead to reduction in base flows due to increased runoff and decline in infiltration of precipitation. Excessive extraction of grounwater in the floodplain or riparian area can lead to instability of river banks causing downcutting of river channels. It can also drastically reduce baseflow severely impacting the low flows during lean season. Inter basin transfer of water also affect the flow in source river. An interplay of all these factors impact the water quality, nutrients supply and populations of freshwater biodiversity in a river basin.

Source of Alteration	Hydrologic Changes	Geomorphic Responses
Dam	Capture of sediment moving downstream	Downstream channel erosion and tributary headcutting Bed Coarsening
Dam, Diversion	Reduced magnitude and frequency of high flows	Deposition of fines in gravel Channel stabilization and narrowing Reduced formation of point bars , secondary channels, oxbows and changes in channel platform
Urbanization, Tiling, Drainage	Increased magnitude and frequency of high flows Reduced infiltration into soil, decline in groundwater recharge	Bank erosion and channel widening Downward incision and floodplain disconnection Reduced baseflows
Levees, Channelization	Reduced overbank flows	Channel restriction causing downcutting Floodplain deposition and erosion prevented Reduced channel migrations and formation of secondary channels
Groundwater Pumping	Lowered water table levels	Streambank erosion and channel downcutting after loss of vegetation stability

Table 1 Physical responses to altered flow regimes (Source: (Poff et al., 1997))

2.3 Ecological Response to Flow Alteration

The physical structure of riverine ecosystem is shaped by variability in flow regime, due to transfer of water, sediments, within the river channel and wetlands in the river basin. The availability of diverse instream and floodplain habitats, helps in evolution of riverine species. According to Bunn and Arthington (2002) aquatic species evolve life history strategies in direct response to natural flow regime. Many life cycle events of fish species (e.g. spawning behavior, reproduction, larval survival, growth pattern,etc.) is synchronized with seasonality of flow regimes.

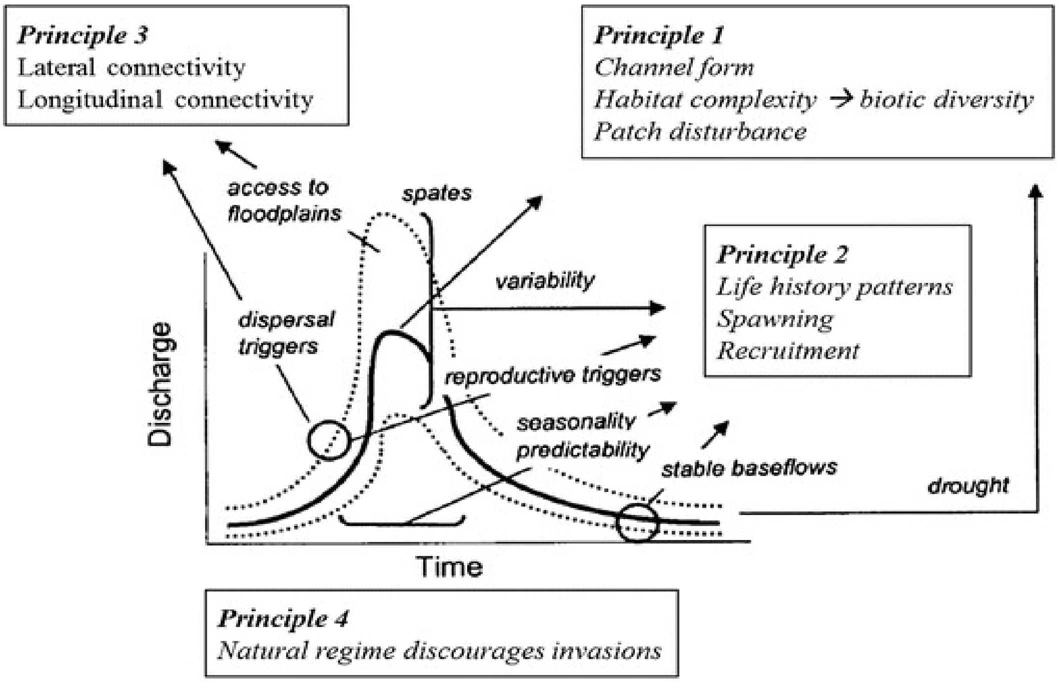


Fig 2.2. Basic principles of influence of flow regime on life history of aquatic biodiversity.
Principle 1 - Flow is a major determinant of physical habitats in streams, which in turn is a major determinant of biotic composition. Principle 2 - Aquatic species have evolved life history strategies in direct response to the natural flow regimes. Principle 3 - Maintenance of natural patterns of longitudnal and lateral connectivity is essential to viability of riverine species. Principle 4 - Invasion and success of exotic and introduced species in riversis facilitated by altered flow regimes (Source: (BUNN & ARTHINGTON, 2002))

Bunn and Arthington (2002) constituted four guiding principles for influence of flow regime on life history patterns of aquatic biodiversity are depicted in Fig 2.2. Alterations in flow components can impact the riverine ecosystems severely. Reduction in frequency and magnitude of floods due to flow regulation can impact the species richness and abundance of freshwater taxa. Loss of connectivity to floodplains (lateral connectivity) affect fish species who migrate to such seasonal wetlands, in search of food and shelter. It can also impact species richness of macrophytes, riparian vegetation, macroinvertebrates that are flow dependent. Natural flooding replenishes soil and nutrients to floodplains making them more fertile for cultivation. Reduced baseflows can increase flow intermittency in river turning perennial river into ephemeral or seasonal in nature. Terrestrialization of river bed by aquatic vegetation can also occur during prolonged low flows period.

In a litreature study of 165 papers it was found that fishes consistently responded negatively to changes in flow magnitude (either increase or decrease) (See Fig. 2.3) (Poff & Zimmerman, 2010). Also, species richness (or diversity) showed a large decline when flow alteration exceeded 50%. A clear response pattern in case of macroinvertebrates and riparian vegetation was not observed. Thus ,fishes can be used as sensitive indicators to changes in flow magnitude, compared to other taxonomic groups like, macroinvertebrates, or riparian species. Ecosystem functional responses (riparian production, nutrient retention, etc.) although largely flow dependent, have not been studied in detail (Zeiringer, Seliger, Greimel, & Schmutz, 2018).

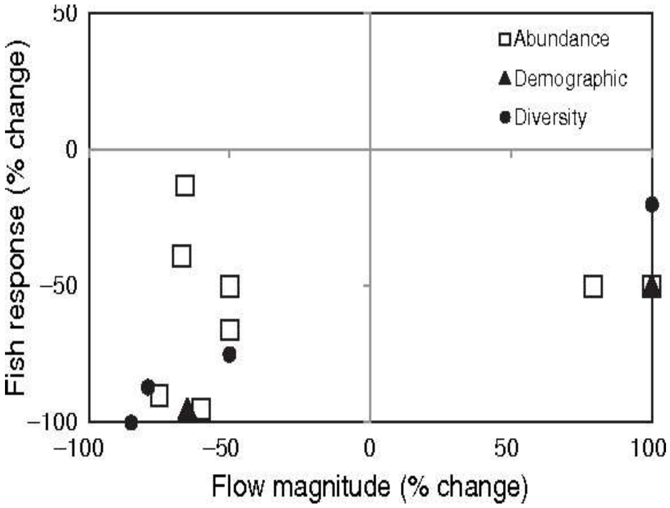


Fig 2.3. Per cent change in fish abundance, demographic parameters and species diversity (or richness) with respect to percent alteration of flow magnitude. (Source: (Poff & Zimmerman, 2010))

Some of the common ecological responses to alteration in flow components were compiled by are summarized below in Table 2. Different taxonomic groups (like, fish, macroinvertebrates, riparian & floodplain vegetation etc.) mostly respond negatively to alteration in flow components.

Flow Compoent	Alteration	Ecological Response	
		Aquatic Organisms	Riparian & Floodplain
Magnitude	Stable flows (loss of high and / low flows) Greater magnitude of extreme high or low flows	Reduction in species diversity and abundance Loss of sensitive species Increase in non-native species Life cycle disruption	Lower Species Richness Altered assemblage and relative abundance of taxa
Frequency	Decreased frequency of peak flows	Reduced Reproduction Reduced habitat for juvenile fishes Decrease in abundance of native species	Reduction in species richness Shift in composition of community
Duration	Decreased duration of floodplain inundation Prolonged low flows / inundation Prolonged Inundation	Decrease in abundance of juvenile fish species Change in fish assemblage Concentration or entrapment of organisms Loss of downstream transportation of organisms Loss of riffle habitat	Reduced growth rate or mortality Reduced plant or forest cover Reduction or elimination of plant cover Diminished plant species diversity Tree mortality Change in functional type of vegetation
Timing	Shift in seasonality of peak flows Loss of seasonal flow peaks	Disruption of spawning cues Reduced reproduction Change in assemblage structure Disruption of migration cues Loss of accessibility to wetlands Modification of food web structure	Reduced plant growth and increased mortality Reduction in species richness and plant cover

Table 2 Alteration in flow components and some common ecological responses of aquatic organisms, riparian and floodplain vegetation (Source: (Poff et al., 1997))

2.4 Environmental Flows

Environmental flow (discharge), also termed as E-Flow, forms the link between river flows and river health. Other terms like water for the environment, environmental water (volume) and ecological flow are also used to describe environmental flows. The concept of environmental flows has evolved from 'minimum flow' necessary for a species and later 'instream flows'. Environmental flow management takes into consideration, lotic, lentic and groundwater phases of all freshwater dependent aquatic ecosystems, including riparian and basin surroundings, to sustain ecological integrity, societal values and ecosystem services derived from it.

2.4.1 Overview of Environmental Flow Assessment Methods

Environmental flow assessment methods are broadly grouped into four main categories - hydrologic, hydraulic rating, habitat simulation and holistic methods. The level of detail increases from hydrologic which are low confidence, rapid, low resolution method to holistic methods which require high data inputs. A summary of all the four categories of e-flow assessment methods is metnioned in Table 3.

Type	Ecosystem Attribute	Requirements	Output	Example
Hydrological	Whole ecosystem condition/health or non-specific	Historical flow records (daily, monthly, or annual). Single flow indices or multiple ecologically relevant flow metrics characterizing flow regime/whole hydrograph Use of historical ecological data , hydraulic habitat data, or meta-analysis of results of multiple environmental water assessments to derive rules.	Flow targets based on estimates of % of annual, seasonal or monthly volume (median or mean) Or as limits to change in vital flow parameters, commonly low flow indices.	Montana Method, Environmental Flow Duration Curve Analysis, Range of Variability Analysis, Desktop Reserve Model (DRM)
Hydraulic Rating	Aquatic (instream) physical habitat for target species or assemblages	Historical flow records; Discharge linked to hydraulic variables, typically single river cross-section Single or multiple hydraulic variables	Hydraulic variables(e.g., wetted perimeter, depth) used as surrogate for habitat flow needs of target species or assemblages	Used within DRIFT, R2Cross Method
Habitat Simulation	Instream physical habitat for target species, guilds ,or assemblages Habitat Suitability	Historical flow records, typically average daily discharge and few to many hydraulic variables Physical habitat availability, utilization and preference data, or similar models for target biota	Weighted usable area(WUA) or similar habitat metrics for target biota Comparative analyses of time series of habitat availability, and duration and use	PHABSIM, IFIM
Holistic	Entire ecosystem All or several ecological components.	Reliant on mix of data and expert judgment, using expert panels. Some use both scientific and traditional knowledge to develop or infer flow-ecology-social relationships.	Recommended hydrological regime linked to explicit quantitative or qualitative ecological ,geomorphological, and Sometimes , social and economic responses and consequences	Building Block Methodology BBM, DRIFT, ELOHA, PROBFLO

Table 3 Summary of Environmentalf Flow Assessment Methods (Source: Adapted from (Poff, Tharme, & Arthington, 2017))

2.4.2 Environmental Flow Assessment in India

In India, Ministry of Environment, Forest and Climate Change (MOEFC) made environmental flow assessment, a mandatory part of Environmental Impact Assessment (EIA), for river valley projects since 2011 (Anantha, Dharmadhikary, & Bhadbhade, 2017). The proposed minimal flow requirement was set as 20% of the average flow observed in the four lean season months at 90% dependability. In 2015, a committee set up by MOEFC, issued a guideline report for Environmental Flows (E-Flows) in India. E-flow was defined as :“ E-flows are a regime of flow in a river that mimics the natural pattern in the river’s flow. It refers to the quantity, quality, and timing of water flows required to maintain the components, functions, processes and resilience of aquatic ecosystems that provide goods and services to people”. The committee proposed, Building Block Methodology (BBM) for estimating E-Flows. This involves developing flow-ecology relationships based on keystone species in a river stretch. A keystone species, according to the committee has large effect on environment relative to its abundance. The methodology requires assessment of temporal variations in flow depth, required for survival and natural growth of keystone species and water requirement for longitudinal and lateral connectivity with floodplains during the monsoon season. It considers the flow depth at riffle as a proxy for minimal water depth requirement of a river stretch. This gives the Minimal Ecological Requirement (MER).

E-flow regime is obtained by mimicking the trend in daily 90% dependable flow using MER for non-monsoon period as E-Flows. Minimum monsoon flow is the flow required for spawning period or maximum flow for non-monsoon period, whichever is greater (Tare, Shekhar,& Singh, 2015). In the above methodology it is assumed that requirement for keystone species will cover for other ecological, social and cultural needs of a river, which may not hold true. Such an assessment has not been completed for any existing or planned dam, irrigation or hydroelectric projects in India (Thakkar, 2015).

2.4.3 Ecological Limits of Hydrological Alteration (ELOHA) Framework

ELOHA is a holistic regional framework for estimation and monitoring of environmental flows based on existing hydrologic, geomorphological , biological and social information. It synthesizes knowledge obtained from several river-specific studies and applies that to other river reaches in a region, where detailed assessments have not been carried out. It is based on the premise that many rivers with similar hydrological and geomorphic attributes may exhibit similarities in ecological response to flow alteration. Flow alteration and ecological response relationships developed, for rivers with different types of hydrological regimes, can then be applied to data deficient river reaches for intial environmental flow recommendations. It can also form the foundation for higher level approaches for environmental flow assessments.

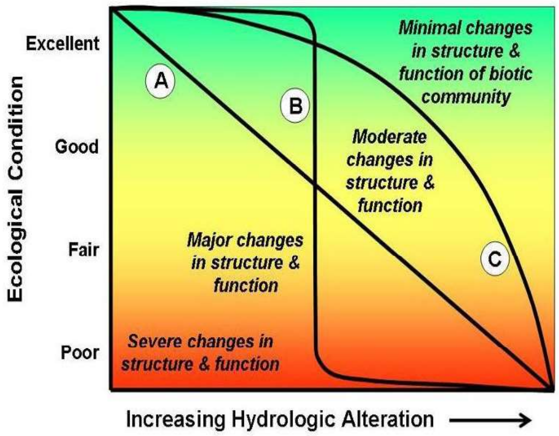


Fig 2.4. Conceptual flow alteration-ecological response relationship (A) Linear (B) Threshold (C) Curvilinear (Source: (Poff et al., 2010))

The ELOHA assessment is carried out in four main steps with feedback loops and iterations (Poff et al., 2010). The main steps are 1) building a hydrologic foundation 2) classifying river segments according to their hydrologic, geomorphic, physical and climatic attributes, 3) computing hydrologic alteration for each river type, 4) developing flow alteration and ecological response relationships by correlating hydrologic alteration with changes in ecological condition. Lastly, environmental flow recommendations are decided based on developed and flow ecology relationships and acceptable ecological conditions set by stakeholders. The goal of ELOHA is to restore the ecological health of rivers while considering the trade-offs between human uses of water and ecological condition of river.

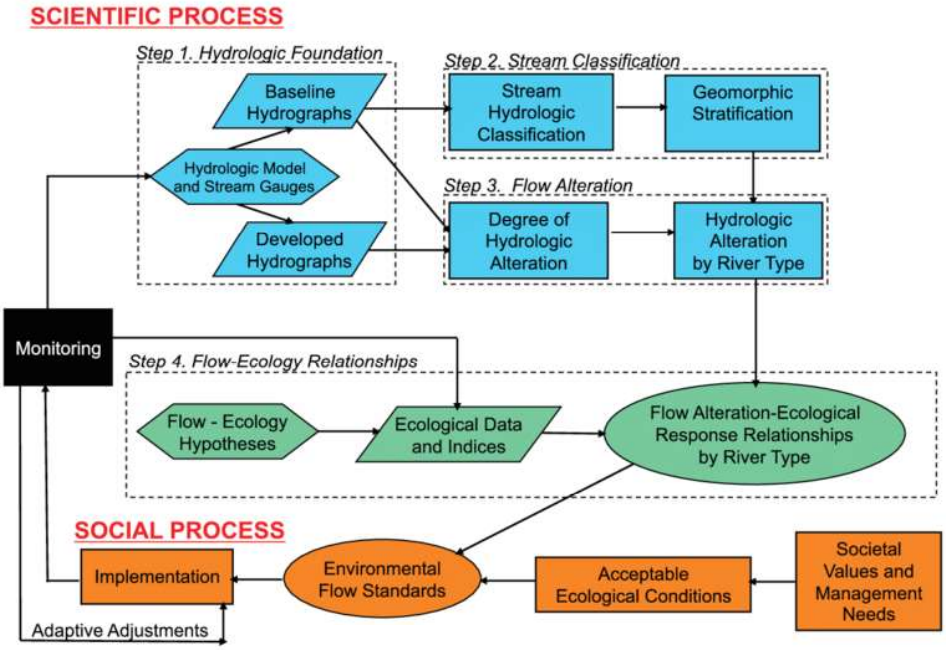


Fig 2.5. The ELOHA (Ecological Limits of Hydrological Alterations) Framework

Hydrological analysis (blue) is carried out in parallel with developing flow alteration-ecological response relationships (green), which provide scientific input to social process (orange) that sets the goals for environmental flow standards.

Source : (Poff et al., 2010)

ELOHA framework is a widely accepted framework for regional environmental flow assessments and has been applied in several river basins for developing flow targets for biotic communities like fishes, benthic invertebrates, aquatic and riparian vegetation, etc. Jeffrey J. Opperman also suggested that ELOHA can be used a preliminary holistic eco-hydrologic desktop method to provide information about flow-ecology linkages and suggest precautinaory flow recommendations (Opperman et al., 2018). Information obtained from a holistic preliminary assessment can identify the crictical locations in a river basin and also guide higher level of environmental flow assessments requiring site specific data collection.

2.4.4 Review of Global Environmental Flow Methods

Existing global environmental flow methods mostly fall into the category of hydrological methods. First global environmental flow assessment was done in 2004 by IWMI (Smakhtin & Eriyagama, 2008). Data from global hydrological WaterGap model at 0.5 degree resolution was used to derive EF requirement based on surface water conditions. Later, an improved version of the method was developed as global environmental flow information system in 2017 for including environmental flows into reporting of SDG indicator 6.4 Water Stress, at an annual timescale (Dickens, Smakhtin, Biancalani, Villholth, & Eriyagama, 2019). Monthly flow data from PCRaster Global Water Balance (PCR-GWB) v2.0 at a resolution of 0.1 degree from time period 1960-2010 was used for deriving natural flow conditions. Natural flow time series data was converted into FDC (flow duration curves) corresponding to 17 fixed probabilities of exceedance.

Environment Management Classes (EMC) from A (natural) to F(Critically modified) were defined to reflect the ecological conditon of a river, based on global 'Incident Biodiversity Threat' index computed by Vorosmarty (Vörösmarty et al., 2010). Originally, four themes of drivers were utilised to calculate this index, namely, watershed disturbance, pollution, water resource development and biotic factors. Global scale spatial data for all the 23 drivers constituded from different sources were resampled to a spatial resolution of 0.5 degree. Downstream propogation of threat or driver value was computed by routing the spatial datasets using global river network, STN-30min (Simulated Topological Network). Routed driver values were normalized by using mean annual discharge from global model,WBMplus. In order to standardised normalized driver values, conversion to a continous scale of 0-1 was done based on cumulative distribution function. For the purpose of global e-flow requirement, only two themes - water resource development and biotic factors, were included and weights were assigned to all the drivers based on judgement by a team of experts. The modified biodiversity threat index map was resampled from 0.5 to 0.1 degree. Value of threat index was arbitrarily grouped into five classes to represent EMCs as A(0-0.25), B(0.25-0.5), C(0.5-0.65), D(0.65-0.7), E-F(>0.7).Environmental flow regime for any EMC was determined by laterally shifting natural FDC stepwise to the left along the probability axis. A minimum possible shift of 1 percentage per EMC has been used.

The main limitation of this method is absence of direct link between ecological condition of a river (i.e, EMC) and environmental FDC derived from lateral shift. Also, seasonality in flow conditions is not considered as e-flow is given as a percentage of mean annual flow/runoff. Different global datasets (for example, PCR-GWB & WBMplus) are used to derive EMC and environmental FDC, increasing sources of error and uncertainity in the analysis. Moreover by using a composite threat index, pressure factors dominant in a river basin cannot be identified increasing ambuigity in interpretation of results. Also, datasets used for calculation of biodiversity threat index are static in nature and are not periodically updated to reflect current ecological condition. Environmental flow FDC defined by this method is fixed till the year 2030, thereby neglecting the dynamic behavior of riverine ecosystems. Though, it is an convenient method to derive environmental flow requirements at a global scale it cannot be redefined at a regional scale to maintain a flow of information or insights from regional to global scale. Using a consistent framework for preliminary environmental flow assessment at both, regional and global scale, will allow us to develop flow alteration-ecological response relationships, establishing link between ecological condition and river flow.

Also, it is necessary to use periodically updated datasets for estimation of threats to ecological condition of rivers, so that these preliminary assessments can be revised every 2-5 years. Pastor also developed two global scale methods, one based on annual flow quantiles (Q90 - Q50 method) and other based on average monthly flows (Variable monthly flow - VMF method) (Pastor, Ludwig, Biemans, Hoff, & Kabat, 2014). In the non-parametric method, Q90 - Q50, e-flows were calculated using Q90 flow quantile during low flow season and Q50 quantile during high flow season. VMF method is parametric one, in which 60% of mean monthly flow (MMF) was reserved during low flow season while 30% of MMF during high flow season. Though, this method considered the flow variability but linkage with ecological condition of the river was missing. Similarly, Hanasaki gave e-flow recommendations as 10 to 40 % of MMF for four different river regimes - dry, wet, stable and variable, respectively (Hanasaki et al., 2008). Another method based on presumptive environmental flow standard was given by Hoekstra and Mekonnen (Hoekstra, Mekonnen, Chapagain, Mathews, & Richter, 2012). A recent global scale study assessing environmental flow limits to groundwater pumping used EFR(environmental flow requirement) as monthly Q90 flow quantile (de Graaf, Gleeson, (Rens) van Beek, Sutanudjaja, & Bierkens, 2019). Though some studies have focussed on separation of surface water and baseflow component for estimation of EFR, still a link with ecological condition of river is missing. Another study set thresholds for EFR based on net primary productivity of fluvial ecosystem on a monthly basis (Shinozaki, Shirakawa, & Fujiwara, 2018). This study used terrestrial NPP as a proxy for fish species richness based on the assumption that there is a positive correlation between fish species richness and terrestrial NPP. This may not hold true as terrestrial NPP is strongly correlated with other climatic factors like temperature and rainfall. It also assumed that terrestrial NPP vary closely with aquatic NPP but there is no strong evidence supporting this assumption.

2.4.5 Environmental Flows : For Sustainable River Basin Management

Environmental flow assessments takes into consideration ecological and scoietal outcomes linked to different water management scenario (King & Brown, 2018).This can be instrumental in sustainble management of water resources. It can timely avert drastic situation like water basin closure due to over-allocation of water resources. Water allocation is mostly done by considering water productivity of a basin and intended benefits from use of water for agriculture, industries, fihseries, hydropower etc., in order to maximize societal or economic outcomes. Equal importance is not given to full range of ecosystem services offered by freshwater resources. This may have led to an understanding, in a section of stakeholders, that water flowing to the sea is "wasted". Many of the river basins in south of India are now closed due to over-allocation of water resources mainly for expanding agriculture, growing high value water intensive crops, meeting industrial and domestic demands etc. For instance, Kaveri basin in India was brought to closure due to expansion of irrigated agriculture and increase in non-agricultural demand for water during the 20th century.

Bhavani basin, a sub-basin of Kaveri basin, was closed even before that in the middle of 1950s (LANNERSTAD, 2008). Lack of surface water, forced irrigation dependent farmers to overextract groundwater resources, further reducing the natural flow in the river, especially, during summer months. Evaporation from stored water in reservoirs also impacted natural flow regime. Closure in one basin can also be transmitted to another basin through inter-basin water transfers. Including environmental flows in water allocation decisions, may avert such a crisis situation. Leaving water for environment will help us to realize the sustainble limits of water exploitation and will force us to practice circular water management.

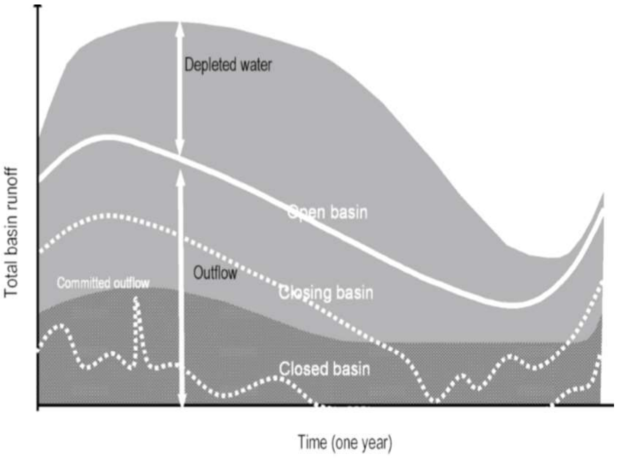


Fig 2.6. Process of River Basin closure over time.
(Source: (FALKENMARK & MOLDEN, 2008))

3 STUDY AREA

This chapter aims to describe the study location. It begins with an introduction about Kaveri river basin, followed by sections on climate and geography, land use, irrigation and cropping pattern,reservoirs and biodiversity. A brief description about Kaveri river dispute is also mentioned in the chapter.

3.1 Study Area : The Kaveri River Basin

Kaveri river is the fourth longest river in South India with a total length of 802 km. It is a peninsular river that originates from a spring, at an elevation of 1341 m, at Talakaveri on the Brahmagiri range in Kodagu district of Karnataka. The east-flowing river meets the Bay of Bengal in the Karaikkal district of Pondicherry. Kaveri river basin has total drainage area of about 81,555 sq km, extending over states of Karnataka (34,273 sq km - 42%), Kerala (2,866 sq km - 4%), Tamil Nadu (43,856 sq km - 54%) and Union Territory of Pondicherry (160 sq km) in south of India. The basin is bounded by Western Ghats on the west, by Eastern Ghats on the east and south and ridges creating a division between Krishna and Pennar basin on the north. The three main physiographic division of the basin are Western Ghats, the Mysore plateau and the Kaveri delta.

Kaveri river system consists of 22 principal tributaries, listed in Table 4. Harangi, Hemavathy, Shimsha and Arkavathi are major tributaries joining the river from the left bank while Lakshmana Thirtha, Kabini and Suvarnavathi flow into Kaveri from the right bank. Further down, Bhavani river joins from the right bank, thereafter the river takes easternly course to enter plains of Tamil Nadu. Noyyal and Amravathi add to the flow of the river down south. Kaveri has total renewable surface runoff of 21.4 cu. km, while potentially utilisable water in the basin is about 27.8 cu km (Amarasinghe,2005). Total population in the basin is 38.76 million according to 2011 census. 676 cu m is the per capita renewable surface water resources while 878 cu m is per capita potentially utilisable water. This implies that basin falls under the category of chronic scarcity according to Falkenmark indicator (Falkenmark, Lundqvist, & Widstrand, 1989).

Kaveri River is one of the most sacred rivers of India and is regarded as "Dakshin Ganga or Ganga of South India. There are many pligramage places along the banks of the river which are of cultural importance to native people. The Kaveri herself is regarded as a goddess and her name implies "one who brings abundance to where she flows". It has also been a source of inspiration for many civilizations which is evident in art, culture and philosophy, originated along the course of the river.

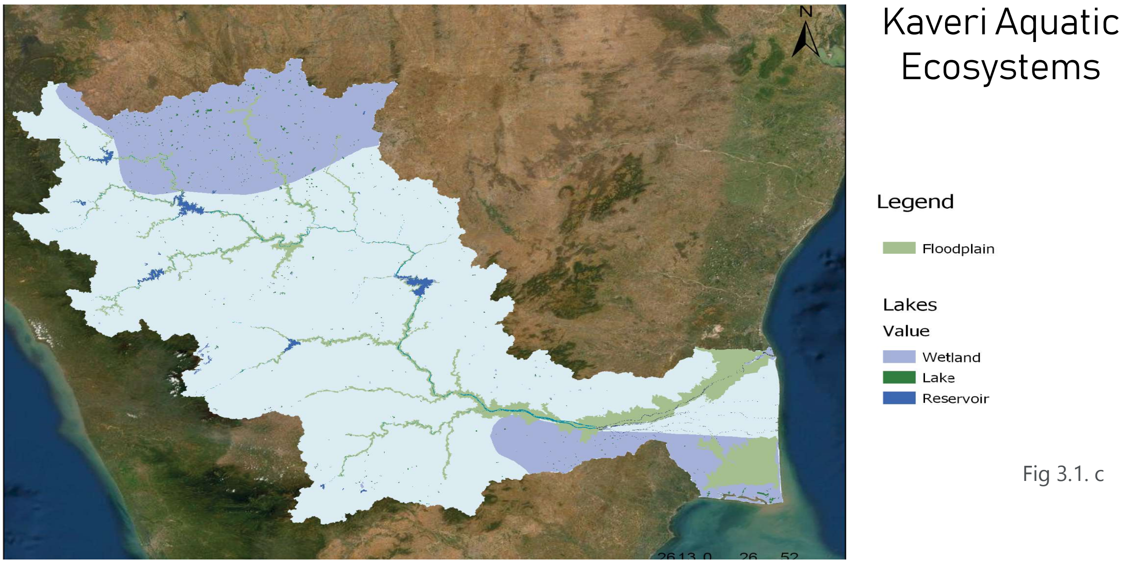


Fig 3.1. c

Name of Tributary	Length (km)	Sub-Tributaries	State	Gauge Stations
Arkavathy	161	Kumudavathi, Manihalla, Kutteholle, Vrishabhavathy	Karnataka & Tamil Nadu	T. Bekuppe
Harangi	50		Karnataka	Kudige
Hemavathy	245		Karnataka	MH Halli, Akkihebbal
Kabini	230	Taraka, Heballa, Nugu, Gundal	Karnataka, Kerala & Tamil Nadu	T. Narasipur, Muthankera
Lakshmana Thirtha	131	Ramathirtha	Karnataka	K M Vadi
Shimsha	221	Veeravaishnavi, Kanihalla, Chickkhole,Habbahalla, Mullahalla, Kanva	Karnataka	TK Halli
Suvarnavathi	88		Tamil Nadu	Bendrehalli
Bhavani	217	Moyar	Kerala, Tamil Nadu	Thengumarhada, Nellithurai, Savandapur
Noyyal	180		Tamil Nadu	E-Mangalam
Amaravathi	282	Nanganji, Kodavanar	Kerala, Tamil Nadu	Nalammaranpatti

Table 4 Principal Tributaries of Kaveri River (Compiled from: ("RIVER SYSTEMS OF KARNATAKA," n.d.))

3.1.1 Climate and Geography

Kaveri basin has four distinct seasons - Winter, Summer, South-West monsoon and North-East monsoon. South-West monsoon sets from middle of June and lasts till September. Majority of rainfall is received by the basin during this season. North-East monsoon lasts from October to November and is important for eastern part of the basin. South-West monsoon is copious and dependable while North-East monsoon supply is irregular and subject to frequent failure increasing agricultural distress in the delta region. There is a significant variation in maximum and minimum daily temperature in the basin with Western Ghats relatively cooler than other parts of the basin and central, eastern & northern regions relatively hotter in summer season. Rainfall received in the basin varies from one region to another. Maximum rainfall occurs in the months of July and August. Mean rainfall received by the basin is around 1075.23 mm in any given year.

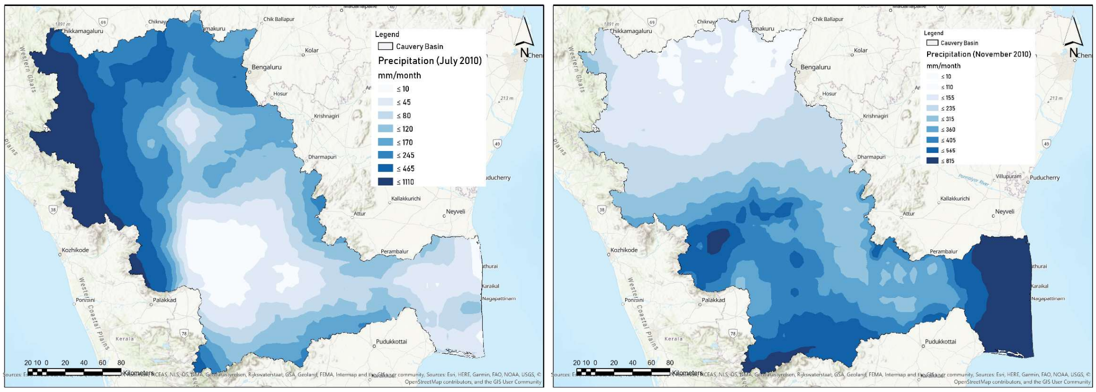
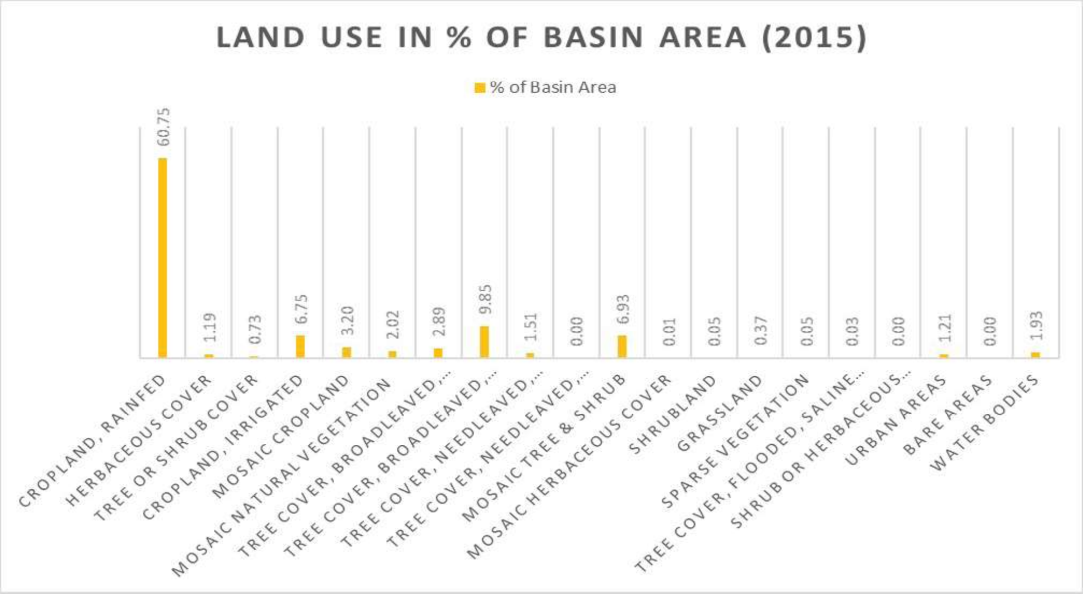


Fig 3.2. Precipitation in Kaveri Basin
July 2010 (Left)
November 2010 (Right)

Data - CHIRPS

3.1.2 Land Use

The spatial distribution of different land use and land cover types in Kaveri basin is shown in Fig. 3.3 . Agricultural land is the dominant land cover type in the basin with rainfed cropland covering 60.75 % of total basin area, followed by broadleaved tree cover with a total of 11.36% of basin area. In the past few decades encroachment of agricultural land into forested area is observed. Water bodies and urban areas occupy 1.93% and 1.21% of land cover in the basin. An increase in urban area is also observed possibly due to an increase in population in the basin.



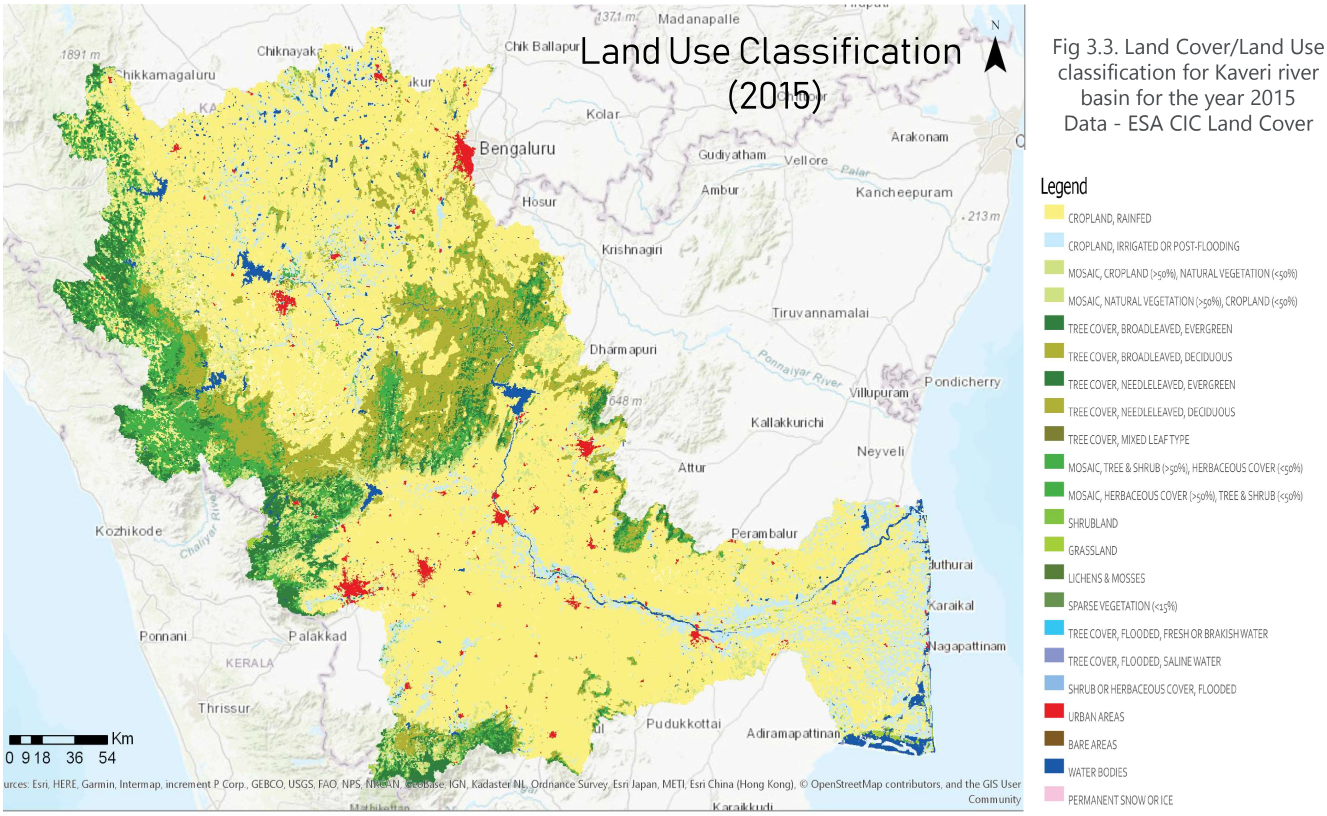


Fig 3.3. Land Cover/Land Use classification for Kaveri river basin for the year 2015
Data - ESA CIC Land Cover

3.1.3 Irrigation and Cropping Pattern

The basin is divided into three agro-ecological zones (See Fig. 3.4):

a) Hot Humid eco-region with red lateritic and alluvium derived soil
(Crops grown: paddy, tapioca, coconut, spices, coffee)

b) Hot Sub-humid to semi-arid eco-region with coastal alluvium derived soil
(Crops grown: paddy, black gram, lentil, sunflower and groundnut)

c) Hot semi-arid eco-region with red loamy soil
(Crops grown: millets, pulses, oilseeds, sugarcane and paddy)

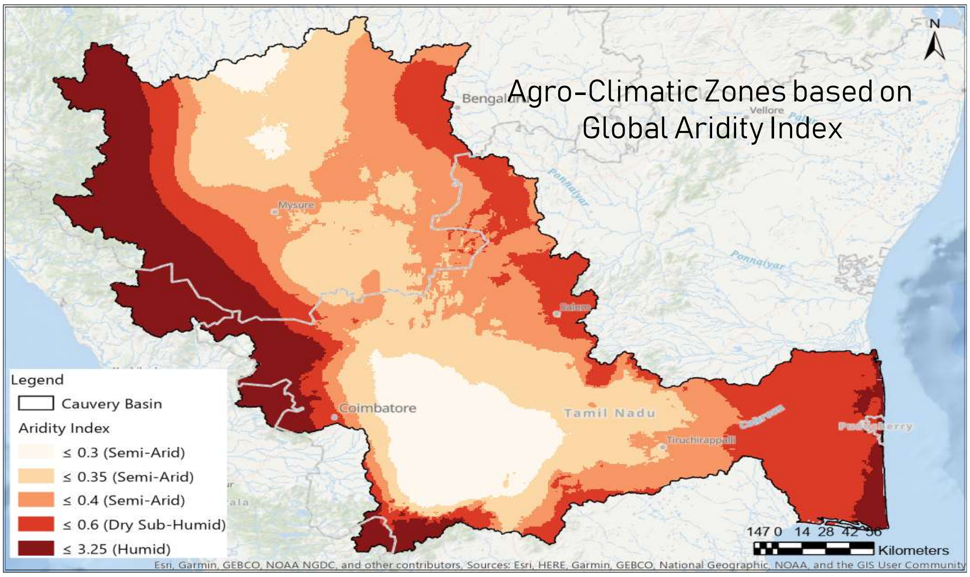


Fig 3.4. Mapping of mean Aridity Index from the period 1950 - 2000. Aridity Index is used to quantify precipitation availability over atmospheric water demand.

Data - Global Aridity Index Climate Database v2

Kaveri basin has three cropping seasons, mainly, kharif, rabi and summer. Paddy, bajra, maize, jowar, ragi, millets, cotton etc. are the main kharif crops cultivated in the basin. Paddy is the pricipal crop grown in the basin while millets like ragi, jowar and bajra are important rain-fed crops. Horticulture crops like coconut, betel leaves, pepper, oranges, and lemon are grown throughout the year.
In Karnataka, paddy is grown in three seasons: Kharif (southwest monsoon), Rabi (winter crop, north-east monsoon) and summer (April-July). In Tamil Nadu, three crops of paddy are harvested every year with varying growing period (Guhan, 1993). Kuruvai is a short duration (105-110 days) rice variety most popular among farmers. It is sown as first crop (June -September) in double crop lands, followed by Thaladi as second crop (October-January) (Guhan, 1993). In single croplands, long duration crop, Samba (August-November) is grown. It is very prominent in the basin and is also grown in dry and semi-dry conditions also.

In Kodagu district, where Kaveri originates, coffee plantation took root in 19th century and has exploded since then due to increasing demand in the international market. This has led to a decline in forest cover by 28% from 2,566 km2 to 1,841 km2 in the region affecting the headwaters of Kaveri river (Nesper, Kueffer, Krishnan, Kushalappa, & Ghazoul, 2017). Most depleted forest type was medium elevation evergreen forest which decreased by 35%. Climate change is also triggering land use change in the region. Shade grown coffee requires predictable rainfall in early months of the year. As rainfall is becoming erratic, farmers are shifting to irrigation, practicing open cultivation and replacing nativer evergreen trees with more exotic Silver Oak trees for proper shade management (Nesper, Kueffer, Krishnan, Kushalappa, & Ghazoul, 2017).

Crop	Rice	Jowar	Bajra	Maize	Ragi	Sugarcane	Total
Water Requirement (in cms.)	150-250	25-30	30-32	50-80	25-30	60-70	-
Area 1991-92	1136908	394835	77867	51510	664151	181105	2506376
Area 1997-78	1254082	294698	32453	67460	624288	178073	2451054
Area 2005-06	1125911	206605	11391	231098	367766	194036	2136807
Area 2012-13	1000504	190171	3500	352365	435043	130490	2112073

Table 5 : Acreages and crop water requirement of major crops in Kaveri basin.
Area mentioned here is in hectares. Source: (Ghosh, Bandyopadhyay, & Thakur, 2018)

3.1.4 Water Resource Projects:

Major multi-purpose water resource projects in the basin are Harangi, Kabini, Bhavani Sagar and Mettur dam. These are used for irrigation as well as for power generation. Kaveri basin houses in total 96 dams built across its river network. A summary of types of water resource structures constructed in Kaveri basin is given below. Pillur dam located on Bhavani river is the highest dam in the basin with a maximum height of 88m and reservoir area of 1191 km^2. Lower Bhavani dam is the longest dam in the basin built across Bhavani river with a length of 8.79 km and reservoir area of 4200km^2. Kabini dam located on Kabini river has a power generation capacity of 20MW and has a reservoir area of 2142 km^2. Mettur dam located in the state of Tamil Nadu has power generation capacity of 240 MW and a catchment area of 42,217 km^2. Grand Anicut also known as Kallanai dam is a simple check dam used for Kaveri delta irrigation project. It is 2000 year old and is regarded as 4th oldest water diversion structure in the world. Hemavathi project located on the tributary Hemavathi river is an irrigation project with a capacity of 1050.63 MCM. Harangi project is a multipurpose project on Harangi river with a reservoir area of 419.58 km^2. Krishnaraj Sagar irrigation project on river Kaveri has a reservoir capacity of 10,619 km^2 and is a major project located in the state of Karnataka.

S.N.	Sub-Basin	Dams	Barrages	Weirs	Anicuts	Lifts	Power Houses
1	Lower Kaveri	2	0	1	3	0	0
2	Middle Kaveri	85	10	3	9	2	23
3	Upper Kaveri	9	0	0	0	7	1

Table 6 : List of Water Resources Projects in Kaveri basin Source: CWC India

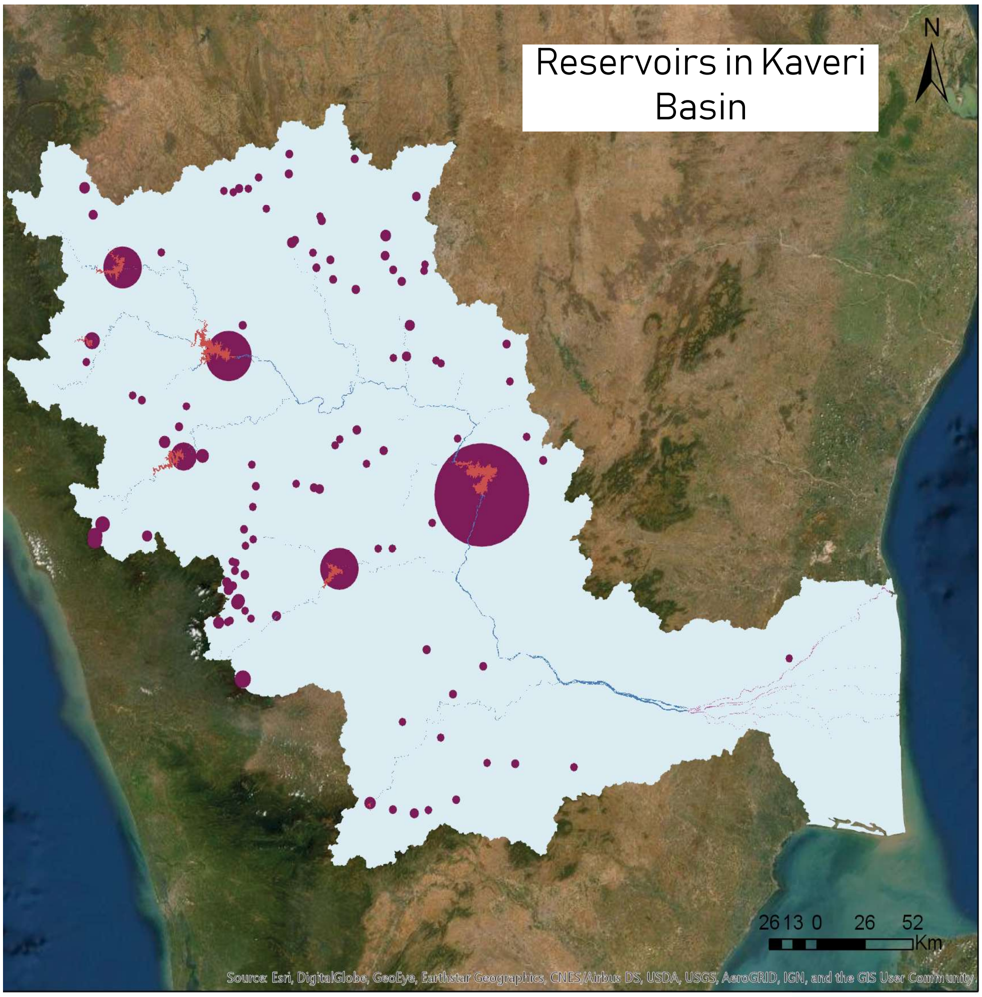


Fig 3.5. Reservoirs in Kaveri basin displayed in proportion to their storage capacity.
Data - CWC India

3.1.5 Century Old Kaveri River Dispute

Kaveri basin is a centre of inter-state dispute over 200 years now, due to conflicting claims by Karnataka and Tamil Nadu on Kaveri waters. This century old dispute stems from the cropping schedule and irrigation development in both the states. There are four main phases in this development.

1. Phase 1 : Prior to Agreement of 1892 –

Irrigation systems in Tamil Nadu existed for atleast last 1800 years. Grand Anicut canal is believed to be built by Chola dynasty in around 200 A.D. The traditional irrigated agriculture of Tamil Nadu depended on monsoon showers from North-East monsoon and canal irrigation. Later Kaveri water was distributed across other districts as well, through new canals and sluice gates. This increased the acreage of crops (paddy, mainly) in the Kaveri delta and made the farmers depended on upstream supply of water for irrigation. Karnataka had a different cropping pattern owing to differences in topography, soil and precipitation patterns. Karnataka grew more of less water intensive crops like millets, while Tamil Nadu is, primarily, a rice producing region.

With the advent of colonial era, their economic interests changed, Karnataka decided to develop its irrigation potential in the mid 19th century. This alarmed the engineers in the Kaveri delta as they feared reduced flows in Kaveri river would harm the paddy cultivation. This led to the agreement of 1892 between Madras Presidency (now, Tamil Nadu) and Mysore state (now, Karnataka) (Guhan, 1993). Karnataka was prohibited from constructing any new irrigation works without the consent of Tamil Nadu government. This was mainly based on prescriptive rights to use of water and favoured the lower riparian state majorly.

2. Phase 2 : 1892– 1934

In 1910, conflicts arose when Karnataka submitted the plans to construct Krishnarajasagara (KRS) dam. As a counter step Tamil Nadu also put forward proposal for Mettur dam. After a lot of conflicts and negotiations, agreement of 1924 was signed. Both the states were granted approval for construction of new dams with strict terms of regulation of discharge from the reservoir and limiting of new area under irrigation.

3. Phase 3 : 1934 – 1974

In this period, irrigation facilities expanded rapidly in both the states. In Karnataka new irrigation developments were recorded due to small reservoirs, anicuts and channels from small tributaries. In Tamil Nadu, irrigation expansion was much more rapid, with several new projects like Amravathy, Pullambadi canal, etc. alongwith Mettur dam increasing the irrigation potential of the region.

4. Phase 4 : 1974 – 1990

The agreement of 1924 came to an end in 1974. Karnataka gave up adherence to rules laid out in the prior agreement and started releasing water from KRS dam based on their needs. New reservoirs damming the tributaries Suvarnavathy, Yagachi, Gundal and Hemavathy also came up during this period. Karanataka followed the theory of absolute sovereignity (Harmon doctrine) for river basin governance (Guhan, 1993). In Tamil Nadu, small scheme projects on sub-tributaries further increased the irrigation command area.

Year	Karnataka		Tamil Nadu	
	Command Area (gross '000 hectares)	Estimated Utilisation	Command Area (gross '000 hectares)	Estimated Utilisation
1901	45	27.2	544	366.9
1928	45	27.2	585	391.2
1971	179	110.2	1024	494.6
1990	866	322.8	1025	501.5

Table 7 - Kaveri Irrigation Development in Karnataka and Tamil Nadu (Source: (Ghosh, Bandyopadhyay, & Thakur, 2018)

Current Situtation :

Following the conclusion of agreement in 1974, rapid expansion in irrigated paddy was witnessed in Karnataka while there was a steady growth in Tamil Nadu state. Dispute over sharing of waters intensified, and as water is state managed subject in India, government of India (GOI) had a tough time in settling the disputes between the two riparian state. There were series of protests and petitions in Supreme court. Regional political parties intensified the conflict for their own interest. Supreme court ordered GOI to set up a tribunal for conflict resolution. After a long wait of 17 years tribunal gave its final award, and allotted, 419 TMC (against demand of 562 TMC) of Kaveri water to Tamil Nadu, 270 TMC (against demand of 465 TMC) to Karanataka, 30 TMC to Kerala and 7 TMC to Pondicherry. Tribunal reserved 10 TMC for environmental protection and 4 TMC for inevitable escapages to sea. Tribunal determined the total utilizable quantity of Kaveri water by considering the 50% dependability of flow at Lower Anicut site. This was based on past hydrological data by eliminating the outlier years with respect to annual rainfall. There was no consideration of variability in rainfall due to climate change and future state of dependability was not predicted. As a result conflicts intensified with Kaveri basin experiencing frequent droughts and underperforming wet years subsequently (See Fig. 3.6). The conflict intesifies during summer months due to increase in cultivation of dry season paddy in both the states. Worsening the problem is a staggering increase in urban water demand in the city of Bengaluru.

Figure: 3.6 SPI (Standardized Precipitation Index) is used to monitor meteorological drought.
1) SPI time series for cumulative periods of 6 months in Tamil Nadu (long 78.6 lat. 9.3).
2) SPI time series for cumulative period of 3months in Karnataka (long.75.5,lat 14.7)
Source: ("MapViewer—Global Drought Observatory—JRC European Commission," n.d.)

A recent order by Superme Court reduced the allocation of water to Tamil Nadu from 192 TMC to 177.25 TMC annually and sanctioned additional water to Karnataka owing to its increasing urban water demand. This was also based on the premise of high groundwater storage in the delta region. Though this move has forced the agriculture sector to practice efficient irrigation water management, it has also made the delta region more vulnerable to salinity intrusion, rising sea levels and land subsidence by encouraging extraction of groundwater. Moreover, silt trapped in dams upstream and sand mining of rivers has decreased the silt content which in turn affects the water holding capacity of downstream regions and causes more flooding and bank erosion. A reductionist approach of allocating water between different states while disregarding the concerns of groundwater overuse, ecosystem degradation and climate variability will further aggravate the dispute. A multidisciplinary approach is required in handling such complex water allocation issues in a water scarce river basin.

4 METHODS

This chapter aims to describe the study region, datasets used in this project, and lastly the methodology adopted for calculation of flow alteration and analysis of flow-ecology relationships.

4.1 Region of Interest

14 gauge stations within Kaveri river basin were selected for the study. Using 30m elevation data from SRTM digital model and gauge station locations, sub-basins were delineated as depicted in Fig. 4.1.

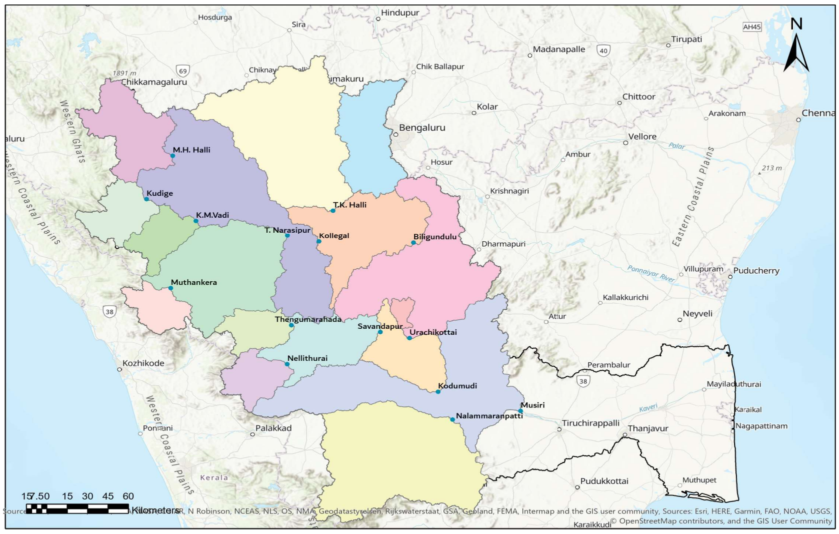


Fig 4.1. Sub-basins delineated in Kaveri basin based on location of gauge stations
Data - CWC India

4.2 Datasets

The datasets used in this study are described below. All the datasets used are freely available at a global scale.

4.2.1 IUCN Red List Spatial Dataset

IUCN Red list is a global repository of information related to species like habitat, range, population size, ecology, threats, etc. to guide conservation actions. Currently, it contains global assessments for 105,732 species and also has spatial data for 75% of assessed species. IUCN's freshwater group consists of following taxonomic groups : fish. molluscs, odonata, plants, crabs, shrimps and cray-fishes. These datasets are periodically updated twice every year depending upon completed regional assessments. Spatial data is available in the form of shapefiles containing the range of each species, depicted as polygons. Taxonomic information, distribution status, IUCN red list category, sources and other details are provided alongwith shapefiles.

Spatial data was downloaded for the Kaveri Basin and species richness maps were produced for each taxonomic groups using SAM (Spatial Analysis in Macroecology) software. Species richness is the count of different species present in an ecological community. It does not takes into account the abundance or population size of any species. Most of the assessments of species in Kaveri basin were completed in the year 2010. This may not be a true representation of freshwater biodiversity of the region as many species become extinct before such assessments are completed.

4.2.2 Free Flowing River Dataset

Free flowing river datatset provides connectivity status of 12 million kilometers of rivers globally. Connectivity status index for each river reach (smallest unit of a river network) was arrived at by considering five pressure factors, namely, a) river fragmentation (longitudnal connectivity), b) flow regulation (lateral and temporal), c) sediment trapping (longitudnal, lateral and vertical), d) water consumption e) infrastructure development. These pressure factors are explained in detail below. River discharge data is provided by long time (1971-2000) average discharge from WaterGap v2.2 global hydrological model while HydroSHEDS and HydroATLAS data is used for other geometric attributes (length, upstream area, etc.). A detailed explanation about calcultion of below mentioned pressure factors is mentioned in "Mapping the world's free-flowing rivers" paper (Grill et al., 2019)

a) Degree of Fragmentation (DOF) indices measures the longitudnal fragmentation of river networks due to dams or irrigation canals. DOF value is scaled between 0% and 100% and was computed for all the individual barriers with the fragmentation effect diminishing in both upstream and downstream. as river size becomes dissimilar. For this analysis, a total of 20,120 dams were included from GRanD (Global Reservoir and Dam) database and GOODD (Global Geo-referenced Database of Dams). Nature fragmentation effect of waterfalls was also considered.

b) Degree of Regulation (DOR) index quantifies the effect of storage of water in dams on natural flow regime of downstream reaches. It is expressed as percentage of river flow volume that can be witheld in a reservoir. A large reservoir on a small river will have large regulatory effect on river flow compared to a small reservoir on a large river. It uses the same set of dams, used in the calculation of DOF.

c) Sediment Trapping Index (SED) quantifies proportion of potential sediment load (PSL) trapped by dams in a river network. In absence of data related to bed load only suspended load was considered. Sediment supply to dams was determined using global erosion (250m) map in the global routing model (HydroROUT). Sediment supply after trapping of sediment in reservoirs was quantified as Modified Sediment Load (MSL).

d) Consumptive Water Use (USE) index takes in to account water consumption for agriculture, industry and domestic usage. It may impact lateral connectivity through reduced flows to riparian areas and effect vertical connectivity by disrupting recharge of groundwater. Over-allocated basins may convert into closed basins, drastically effecting the longitudnal connectivity of river. Timing and seasonality of water abstractions alters the temporal connectivity. Data from WaterGap was used for this analysis.

e) Road Density (RDD) is used as a proxy for lateral disconnection from floodplains at intersections with streams due to culverts. Vector dataset provided by GRIP (Global Road Inventory Project) was used. Road density was summarized within a buffer area of 1km around each river reach, as percentage of surface area covered using an average river width of 50m.

f) Urban Areas (URB) Infrastructure development in floodplain areas can reduce the lateral river connectivity due to presence of impervious surfaces. Global dataset of nighlight intensity (DMSP-OLS v4) was used as a proxy for urbanization extent in contributing sub-catchment of each river reach.

4.2.3 Precipitation

The quasi global , 0.05 degree resolution gridded precipitation series from Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) (Funk et al., 2015). The dataset was used to study the effect of seasonality of precipitation on gross primary prouctivity, hydrological alteration and other climatic variables. Monthly data for the time period - (2003 - 2010), was downsclaed to a resolution of 500 m and used for the analysis.

4.2.4 Actual Evapotranspiration

Evapotranspiration is an important component in terrestial water balance, especially in arid and semi-arid regions. Monthly actual evapotranspiration data from Simplified Surface Energy Balance (SSEBop) (Senay et al., 2013) model was used for the analysis. Data was downscaled to 500m resolution using bi-linear interpolation technique for comparison with other variables depicting vegetation dynamics and water availability.

4.2.5 Primary Productivity & Enhanced Vegetation Index

In order to study vegetation dynamics of floodplain vegetation and relate it with hydrological alterations and climatic conditions, gross primary productivity (GPP) (MOD17A2H.006) and enhanced vegetation index (EVI) (MOD13A1.006) parameters at 500m resolution were chosen. Gross primary productivity is the rate at which organic matter is produced by plants per unit area in time while net primary productivity is GPP minus rate of energy loss due to metabolism and maintenance. Net primary productivity data can also be used in this analysis but it is currently unavailable due to errors in the input data. EVI is calculated similar to NDVI but it has been corrected for distortions caused due to particles in air and ground cover below vegetation.

4.2.6 River Discharge

Monthly river discharge data was taken from the global hydrological model PCR-GLOBWB v1.0 (PCRaster Global Water Balance Model). Kaveri basin is a highly modified basin and there is no record of natural river discharge which can be taken as reference for flow regime alteration calculation. Hence, discharge data from PCR-GLOBWB model was taken as natural discharge at every gauge station location. Observed flow data at gauge stations was provided by Central Water Comission of India.

4.2.7 Land Use/Land Cover

A high resolution (300m) yearly land cover maps are developed under ESA(European Space Agency) Climate Change Initiative (CCI) (“ESA/CCI viewer,” n.d.). Land cover classification system developed by United Nation’s FAO (Food and Agriculture Organization) is adopted in this product. These yearly datasets are available from 1992 to 2015. Separate land cover maps for epochs 2000, 2005 and 2010 are also freely available. Land cover maps from 2000 to 2010 were used in the study.

4.2.8 Global Floodplain Dataset

A high resolution (250m) gridded dataset of floodplain extent (GFPLAIN250m) (Nardi, Annis, Di Baldassarre, Vivoni, & Grimaldi, 2019) was used for selecting the sampling points lying inside the floodplain area around each gauge station. SRTM (Shuttle Radar Topography Mission (SRTM) digital model was used for geomorphic floodplain delienation.

4.2.9 Global Surface Water Explorer

Global surface water explorer dataset documents surface water occurence and seasonality by processing Landsat imagery over the past 32 years (1984-2015) at 30 m resolution (Pekel, Cottam, Gorelick, & Belward, 2016). Long term water history can depict the changes in surface water dynamics due to natural or anthroprogenic factros. Layer depicting transition in river behaviour (ex. perrenial, epehemeral, seasonal,etc.) from first to last year of observation was used in this study. This dataset is regularly updated.

4.2.10 Global River Classification

A global database of river classification based on hydrologic, physio-climatic and geomorphic factors was used in the study to group the representative river reaches with similar environmental characteristics. A global river classification dataset (GLORIC_250m) (Dallaire, Lehner, Sayre, & Thieme, 2019) can help in extrapolating characteristics like flow alteration and ecological response curves to data defecient river reaches. This can expedite preliminary environmental flow assessments in highly impacted river basins with limited data and resources.

4.3 Methodology

4.3.1 Monthly Hydrological Alteration in Magnitude

Assessing the deviation of river streamflow characteristics from the natural flow regime is required to study the impact of altered flow regime on the riverine ecosystem. Regional approaches for quantifying hydrologic alterations are usually based on daily streamflow data. In order to determine the hydrologic alteration at monthly time scale,a method proposedby ISPRA(Italian governmental authority Higher Institute for Environmental Protection and Research) was adopted (Pumo, Francipane, Cannarozzo, Antinoro, & Noto, 2018).Monthly hydrological alteration in magnitude at the location of 14 gauge stations was calculated by considering 12 parameters, one for each month (January-December). Monthly flow data from PCR-GLOWB model was used as reference natural flow while daily ground observations of river discharge were used as impacted flow. Daily observations were aggregated to calculate monthly flow data for each year. All the available hydrological records were used in the analysis. Inter-annual flow statistics, median, 25th percentile and 75th percentile of monthly flows was determined both for impacted and natural flow data. Deviation of inter-annual statistics (median) of impacted flow, from target range defined by inter-annual statistics (25th percentile & 75th percentile) of natural flow data was calculated as described below.

Monthly Indicator, $p_{(i)} = \min\{| (XP_{(i)} - XN_{(25,i)})/ (XN_{(75,i)} - XN_{(25,i)}) , (XP_{(i)} - XN_{(75,i)})/ (XN_{(75,i)} - XN_{(25,i)})|\}$

where, $XN_{(75,i)}$ and $XN_{(25,i)}$ are 75th and 25th percentiles,respectively, computed over natural flow time series while $XP_{(i)}$ is the median of monthly flow computed over impacted flow time series. Average of monthly indicators $p_{(i)}$ for all the 12 months gave a composite index for hydrological alteration in magnitude of monthly flow conditions.

4.3.2 Analysis of Flow-Ecology Relationship

For assessing flow ecology relationship between gross primary productivity and hydrological alteration in a basin an exploratory data analysis was done. In order to assess the influence of climatic condtions variables like rainfall and actual evapotranspiration were used. Using global floodplain dataset as a boundary layer, 50 data points, in the riparian and floodplain region, near each gauge station were selected. Data for gross primary productivity, actual evapotranspiration, rainfall and enhanced vegetation index were extracted for all the selected 700 data points. Land use type for all the selected points were checked using MODIS Land Cover data. Points with same land use type over the analysis period (2003-2010) were finalized. Two land use types were mainly assessed, croplands and grasslands. 8-day gross primary productivity (GPP) and enhanced vegetation index (EVI) data was aggregated into monthly data. Median of all selected points at a gauge station was calculated for all the variables. Finally, inter-annual statistics, i.e, monthly median value for all the variables, GPP, EVI, rainfall and actual evapotranspiration was calculated for all the 14 gauge stations. All the variables were plotted for each gauge station to study the seasonal variation and correlations between GPP , EVI and hydrological alteration, rainfall and actual evapotranspiration.

5 RESULTS & DISCUSSION

5.1 Adapted Framework for Global E-Flow Assessment

Based on findings of litreature review, it was decided that ELOHA framework will be adapted, using available open-source global datasets, so that it can be used for developing preliminary environmental flow recommendations at a global scale.The adapted framework (See Fig. 5.1) consists of 7 steps and has been developed on the lines of ELOHA framework. Building a hydrologic foundation for e-flow assessment is the first step and forms the basis of the assessment. It is recommended that all the available flow records should be used in the assessment, instead of limiting the data to a 15 or 20 years window. In a highly modified river basins where natural flow data or data before the disturbance period is not available, modelled flow data from global hydrological models can be utilised. Disturbed or modified flow regime can be inferred from flow data from gauge stations or can be derived from hydrological models. Next, river segments are classified according to their physical-climatic, hydrologic and geomorphic attributes. A global river classification framework,GloRic, developed by Camille Ouellet Dallaire and Bernhard Lehner, can be utilised to identify groups of rivers with similar characteristics (Dallaire, Lehner, Sayre, & Thieme, 2019). Third step consists of calculation of flow alteration, using monthly hydrological alteration indicators as explained in Section 4.3.1. In the next step ecosystem integrity of a river segment is assessed using biotic and abiotic indicators. Four categories of indicators - Connectivity Status, Biodiversity, Land Use and Water Quality, have been proposed for estimation of ecoystem integrity of rivers. These indicators are explained briefly in subsequent sections. Due to unavailability of global datatset for inland water quality it has not been included in this study. Data from world water quality portal can be utilised in future. Flow alteration and ecological response relationships can then be developed using hydrological alteration index and suitable ecosystem indicators. For easier comparison ecosystem integrity indicators are organized in respective environment management classes. Critical sub-basins in a river basin and dominant pressure factors impacting the river segment can be identified based on this preliminary assessment. A precautionary environmental flow recommendations at monthly time step can be set according to thumb rule or through flow alteration and ecological response relationships. Setting up of environmental flow recommendations could not be completed in this study. The components of adapted framework are discussed in detail through a case study of Kaveri river basin.

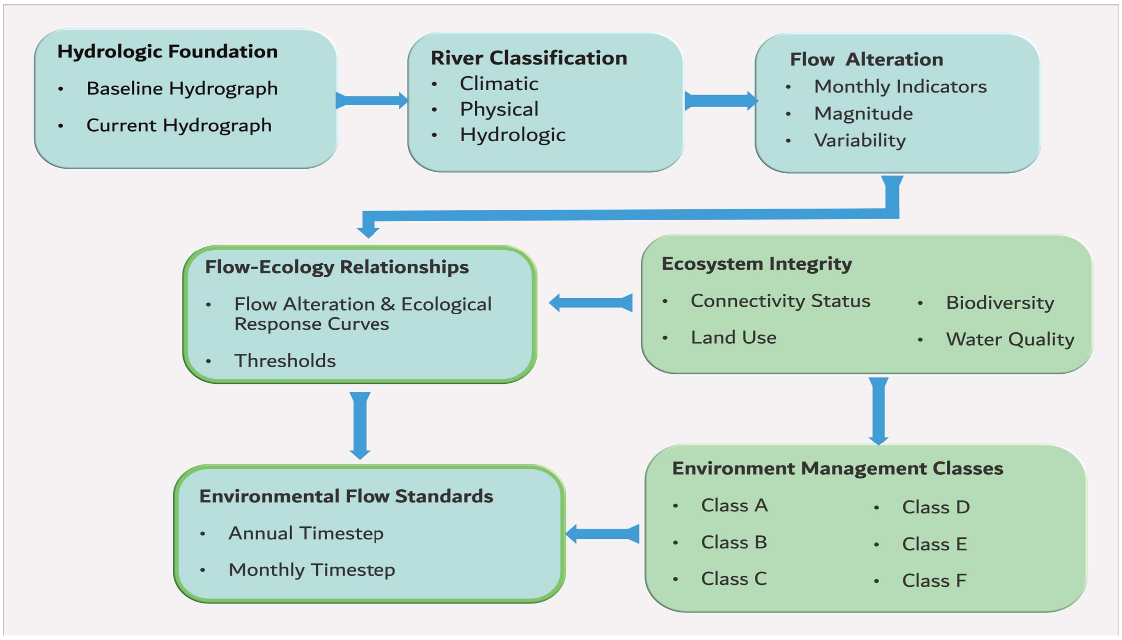


Fig 5.1. Adapted ELOHA Framework for preliminary holistic environmental flow assessment.

5.2 River Classification

The river reach classification for Kaveri basin is based on Global River Classification (GloRic) framework(Dallaire, Lehner, Sayre, & Thieme, 2019). A subclassification of river type was first develped based on indices or attributes belonging to different categories - hydrologic, geomorphic and physio-climatic. The sub-classifications are then combined to get a holistic classification of river segments. At respective gauge location river classes were identified. The sub-classifications for Kaveri river basin are mentioned in Appendix 1. Gauge stations in Kaveri river basin were organized in 8 river classes as shown in Table 8. The main stem of the river, on which stations Kollegal, Biligundulu, Urachikottai, Kodumundi and Musiri are located belong to river class 732, and is categrorized as medium river with medium or high stream power in a very hot, low mositure region.

S.N.	River Class	Physio-Climatic	Hydrologic	Geomorphic	Gauge Stations
1	732	very hot, low moisture region	medium river	medium and high stream power	Kollegal, Biligundulu, Urachikottai, Kodumundi, Musiri
2	731	very hot, low moisture region	small river	medium and high stream power	T. Narasipur
3	721	very hot, low moisture region	small river	low stream power	Thengumarhada, Savdanpur, Nalammarapati
4	711	very hot, low moisture region	very small river	low stream power	T K Halli
5	712	very hot, low moisture region	very small river	medium and high stream power	Nellithurai
6	1021	hot and very hot, high elevation region	very small river	medium and high stream power	K M Vadi
7	1022	hot and very hot, high elevation region	small river	medium and high stream power	Kudige
8	1023	hot and very hot, high elevation region	small river	lake-wetland influenced	M H Halli

Table 8 - River Classes identified in Kaveri river basin as per GloRic framework

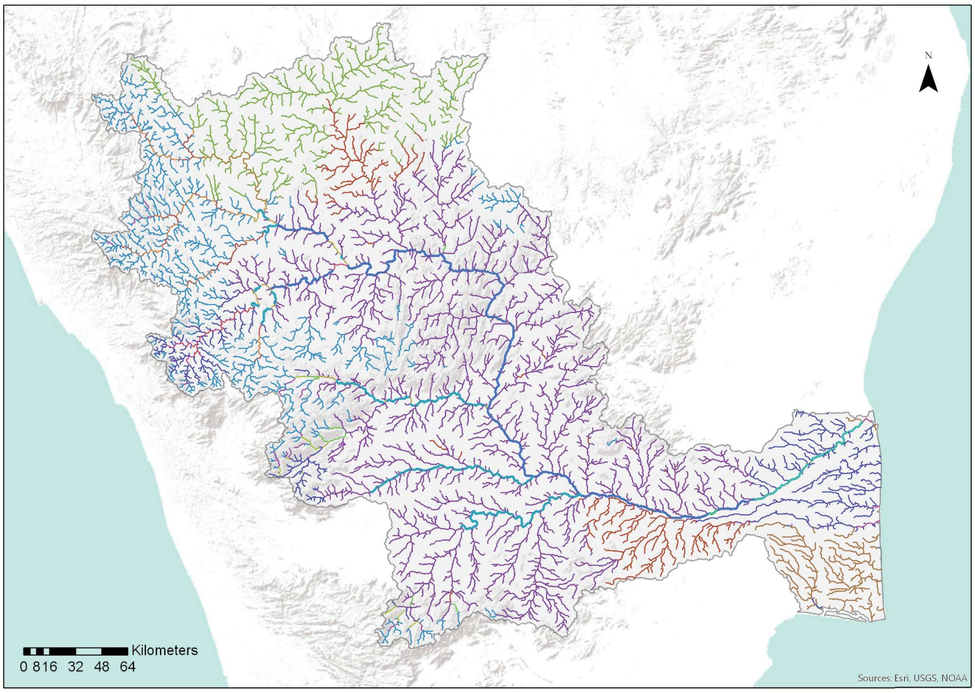


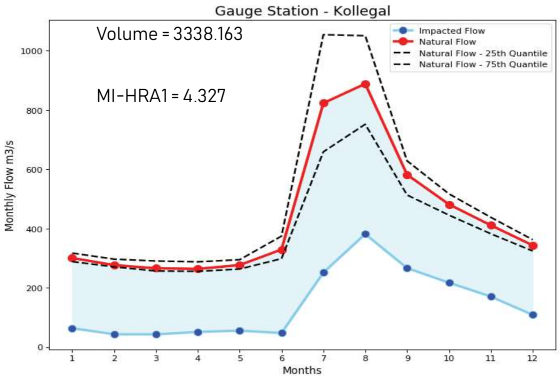
Fig 5.2. GloRic River classification for Kaveri basin.
Data - GloRic

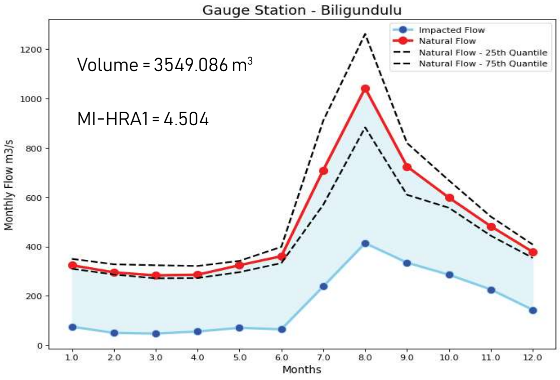
5.3 Hydrological Alteration in Magnitude

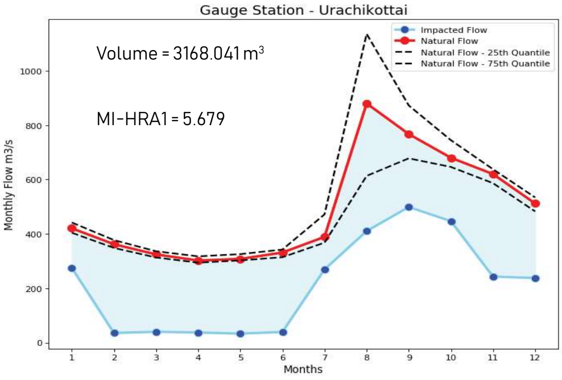
Monthly Hydrological alteration in magnitude was calculated for 14 gauge stations in the basin (See Table 9). All the available hydrological records available at each station were included in the analysis. A significant departure from reference natural flow conditions was observed at most of the locations in the basin. A large reduction in baseflow was observed at all the gauge stations located on the main stem of the river which signals at high rate of water abstraction or diversion from the source river. A similar trend in alteration of flow regime was observed as we moved from upstream gauge station Kollegal, to the last gauge station Musiri, located in the delta region of the basin. Baseflow in summer months dropped to very low levels, almost like zero flow conditions, while high flows during monsoon season were also reduced and stabilised, possibly because of flow regulation. This is also confirmed by results obtained from the analysis, transitions in river behavior (See Fig. 5.4) which shows that Kaveri river, which was once a perrenial river has now turned into a seasonal river. As we move from upstream to downstream portion of the river the proportion of permanent water in a river stretch is declining steadily from 29.1% near Kollegal to nearly 4% near Musiri in the delta region. Salt water intrusion at the mouth of the delta was also observed (Fig.5.4-10c) This shows that as Kaveri basin turned into a closed basin, coupled with high abstraction of groundwater in the delta region, seawater ingressed several kilometers inside making freshwater unfit for use due to increase in salinity in the region.

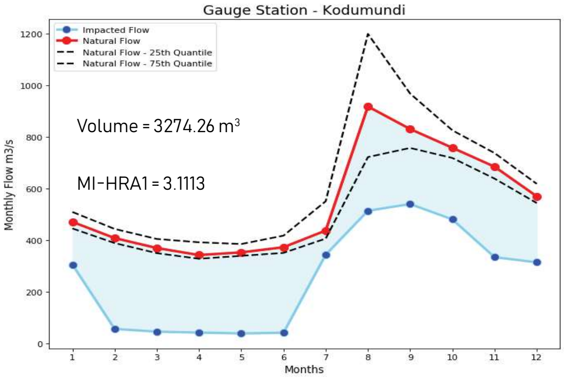
Fig 5.3. Hydrological Alteration in Magnitude at 14 gauge stations in Kaveri river basin. Red lines and markers refer to reference natural flow while blue line and marker refer to observed flow conditions. Black lines are the 25th and 75th percentiles of natural flow. Coloured region depicts the volume of water consumed or diverted causing deviation from natural flow regime.

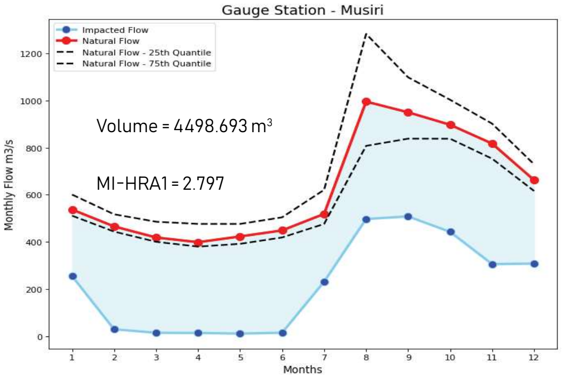
(Data - Natural Flow - PCR-GLOBWB v1 Observed Flow - CWC India)
(Source: Author)

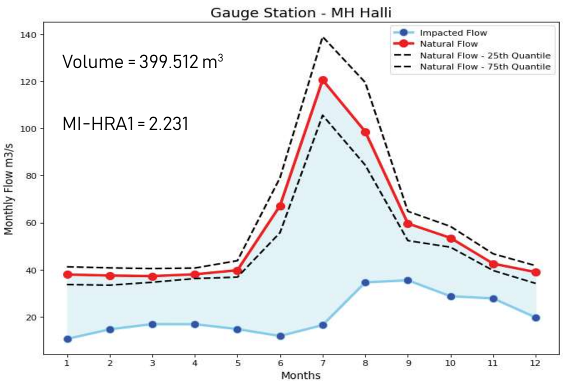








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Natural Flow
Natural Flow - 25th Quantile
Natural Flow - 75th Quantile
Monthly Flow m3/s
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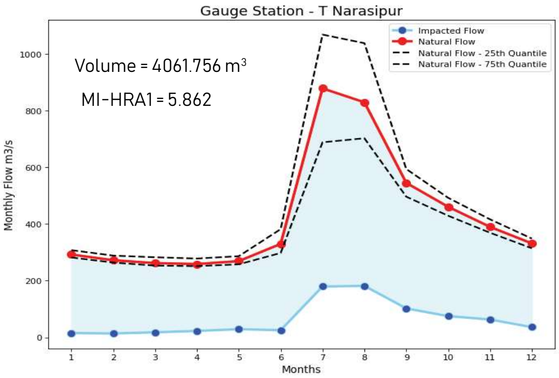
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Natural Flow
Natural Flow - 25th Quantile
Natural Flow - 75th Quantile
Monthly Flow m3/s
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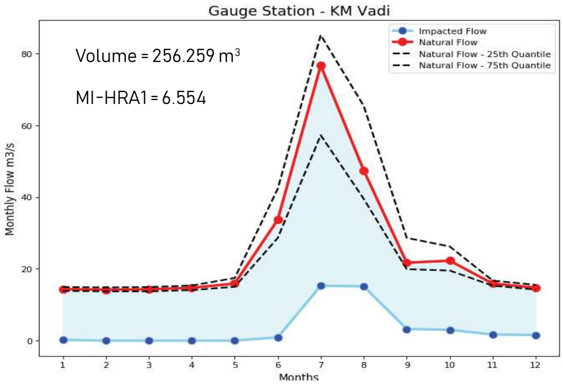
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MI-HRA1 = 6.554
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Natural Flow
Natural Flow - 25th Quantile
Natural Flow - 75th Quantile
Monthly Flow m3/s
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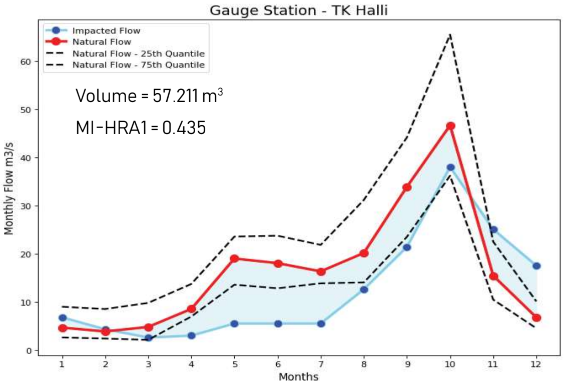
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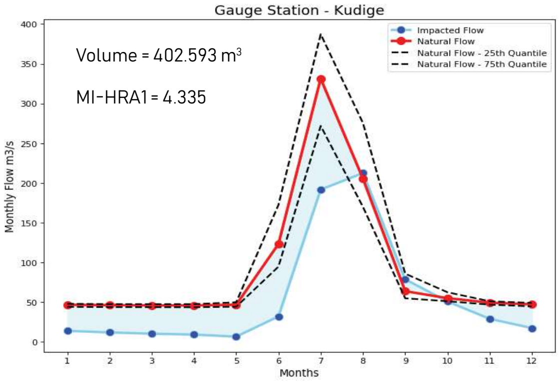
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MI-HRA1 = 4.335
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Natural Flow
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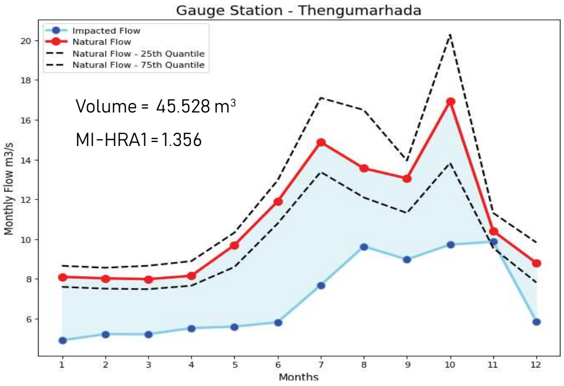
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MI-HRA1 = 1.356
Impacted Flow
Natural Flow
Natural Flow - 25th Quantile
Natural Flow - 75th Quantile
Monthly Flow m3/s
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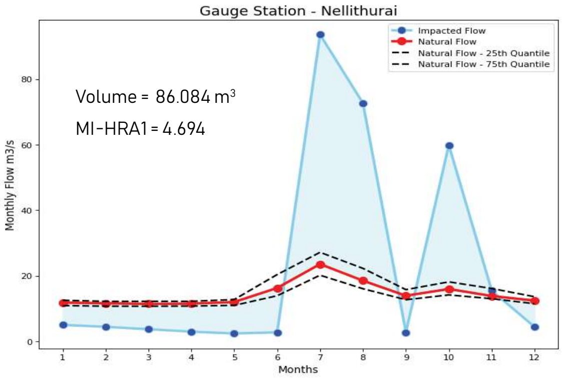
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MI-HRA1 = 4.694
Impacted Flow
Natural Flow
Natural Flow - 25th Quantile
Natural Flow - 75th Quantile
Monthly Flow m3/s
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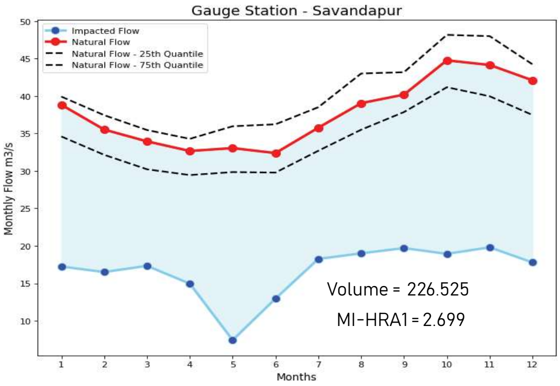
Gauge Station - Savandapur
Volume = 226.525
MI-HRA1 = 2.699
Impacted Flow
Natural Flow
Natural Flow - 25th Quantile
Natural Flow - 75th Quantile
Monthly Flow m3/s
Months
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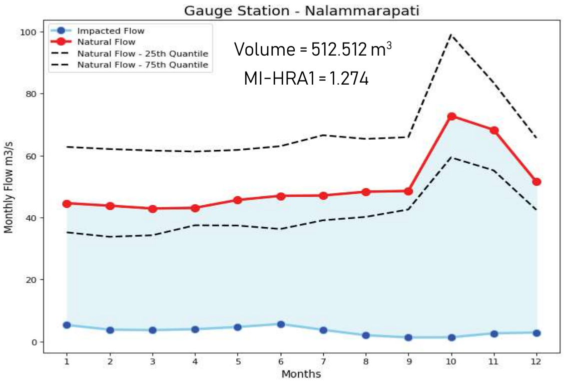
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MI-HRA1 = 1.274
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Natural Flow
Natural Flow - 25th Quantile
Natural Flow - 75th Quantile
Monthly Flow m3/s
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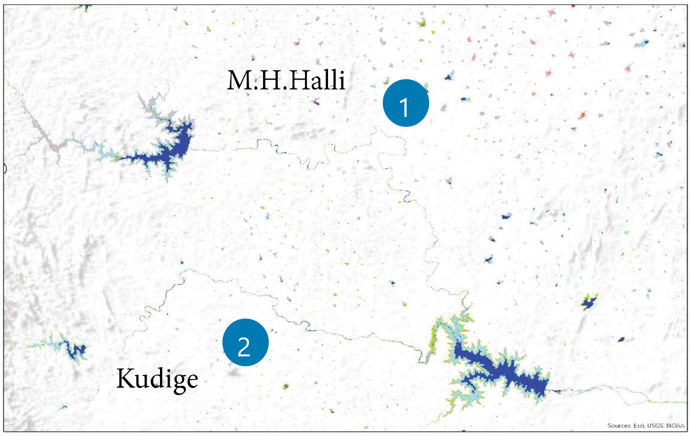
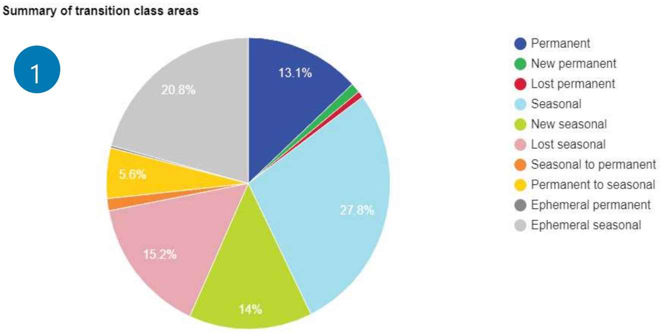
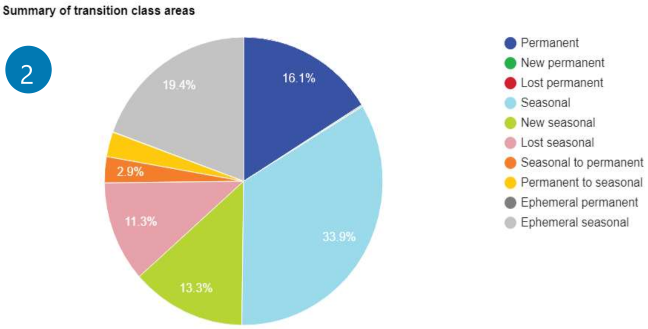
Table 9 - Results of monthly hydrological alteration in magnitude at 14 gauge stations in Kaveri

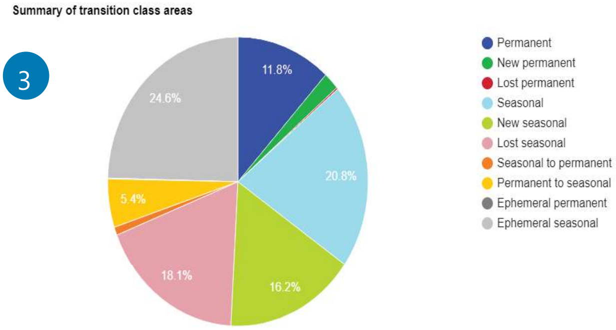
Gauge Stations	M.H. Halli	T. K. Halli	Kudige	K. M. Vadi	Biligundulu	Kollegal	T. Narasipur	Urachikottai	Thengumarhada	Savandapur	Kodumundi	Nellithurai	Musiri	Nalammaranpati
Years	(1979 - 2010)	(1979 - 2010)	(1974 - 2010)	(1980 - 2010)	(1972 -2010)	(1972 - 2010)	(1972-2010)	(1980-2010)	(1980-2010)	(1979-2010)	(1972-2010)	(1980 - 2010)	(1973 - 2010)	(1979-2010)
Ind	Ind	Ind	Ind	Ind	Ind	Ind	Ind	Ind	Ind	Ind	Ind	Ind	Ind	Ind
P (1,1)	2.811	0.398	7.607	12.606	6.346	6.954	9.314	3.067	2.388	3.184	2.084	3.422	2.783	1.007
P (1, 2)	2.323	0.301	8.169	12.48	5.973	7.712	9.399	10.172	2.045	2.851	5.807	4.008	4.219	0.976
P (1,3)	2.602	0.069	8.523	11.103	4.720	5.813	7.299	11.554	1.763	2.207	5.091	4.312	3.813	0.997
P (1,4)	3.483	0.561	8.514	10.516	5.153	6.101	7.800	9.857	1.623	2.716	4.255	5.280	3.617	1.297
P (1, 5)	2.943	0.785	6.599	5.919	4.069	5.785	7.109	10.295	1.681	3.596	6.371	4.656	4.325	1.203
P (1, 6)	1.844	0.644	0.753	1.954	4.831	3.251	3.067	9.338	2.195	2.416	4.115	1.663	4.414	0.976
P (1, 7)	2.585	1.010	0.596	1..248	1.446	0.951	1.298	0.842	1.434	2.399	0.352	9.161	1.184	1.149
P (1, 8)	1.269	0.037	0.392	0.871	2.239	1.143	1.438	0.356	0.536	1.881	0.395	7.702	0.515	1.267
P (1, 9)	1.252	0.091	0.294	1.646	2.673	2.032	3.803	0.847	0.731	3.249	0.978	3.136	0.924	1.714
P (1, 10)	2.232	0.064	0.016	2.259	4.697	2.971	5.183	1.936	0.548	2.712	2.016	10.088	2.065	1.337
P (1, 11)	1578	0.158	3.838	8.082	5.404	3.616	6.124	5.983	0.204	2.311	2.989	0.233	3.051	1.806
P (1, 12)	1.806	1.191	6.091	9.521	6.219	5.410	7.757	4.398	0.949	2.862	3.015	3.206	2.540	1.602
MI-HRA 1	2.231	0.435	4.335	6.554	4.504	4.327	5.862	5.679	1.356	2.699	3.113	4.694	2.797	1.274

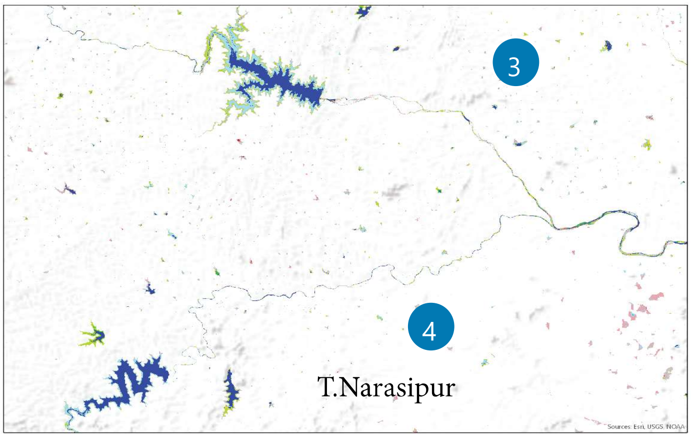
Fig 5.4. Transitions in river behavior in time period 1984-2015.
Kaveri river network is divided into 10 sections and surface water classes based on long term water occurence data is depicted in pie charts. Reservoirs were excluded from the analysis in order to assess the transition in behavior of river streches alone.
Data - JRC Global Surface Water Explorer

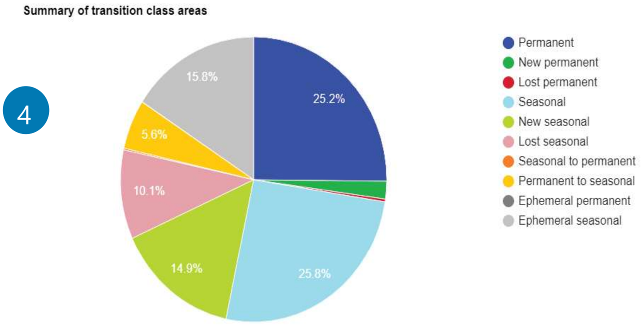


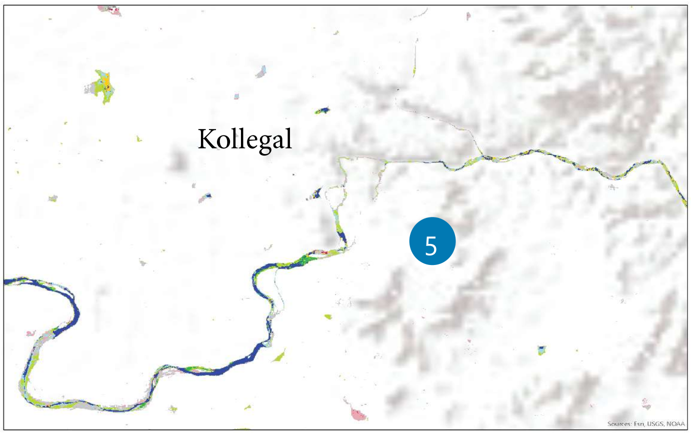


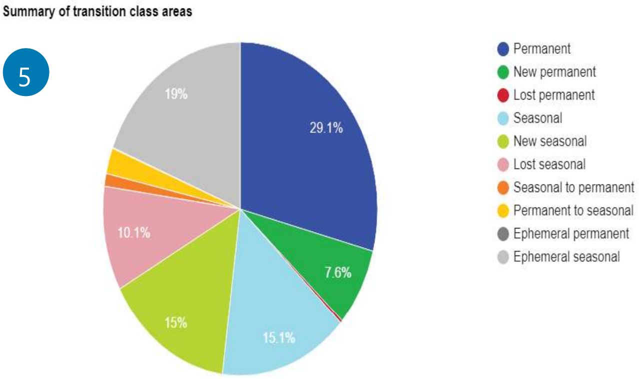


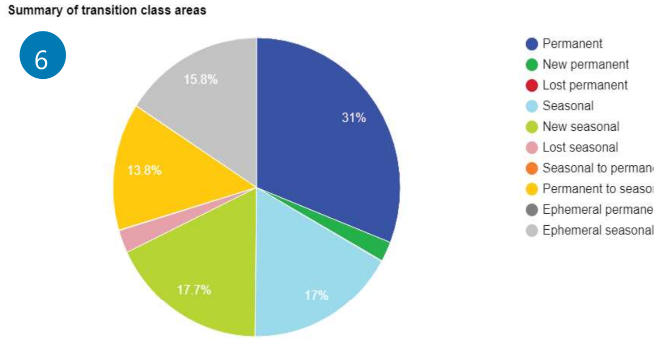


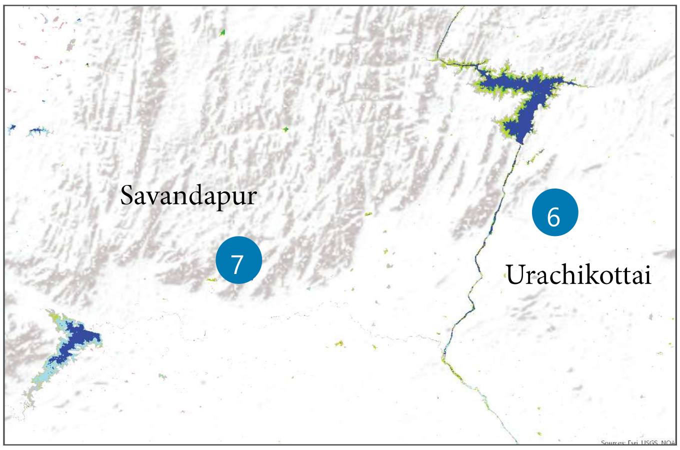


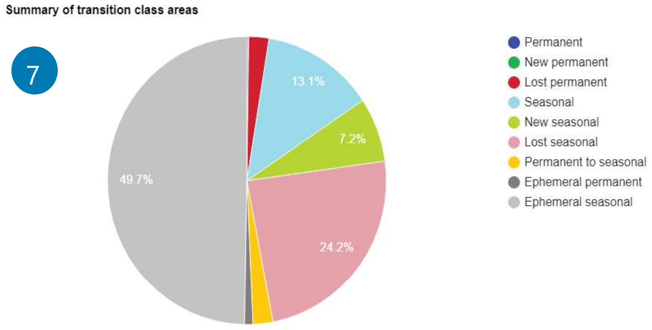


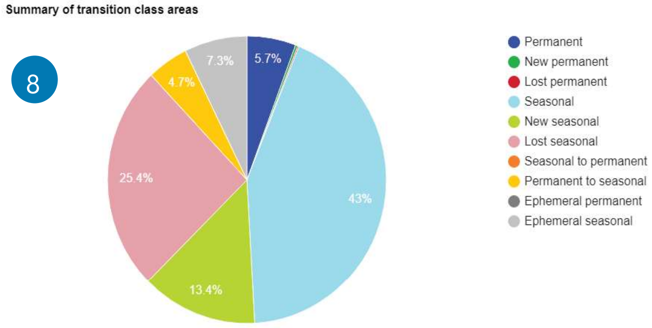


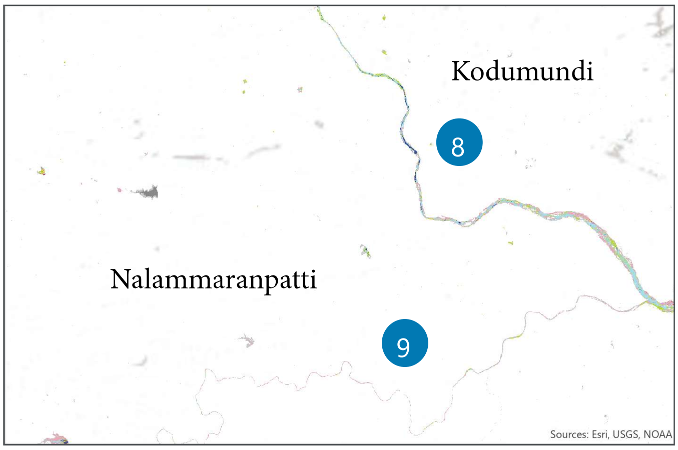


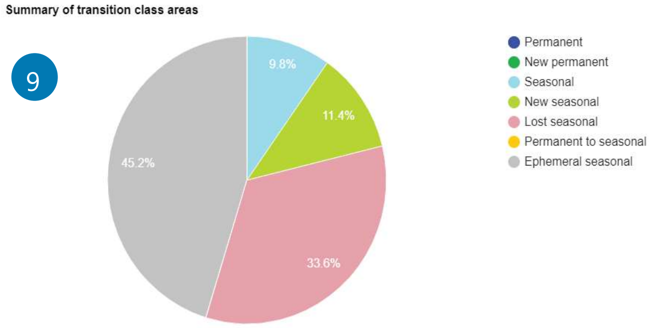

Summary of transition class areas
6
31%
17%
17.7%
13.8%
15.8%
Permanent
New permanent
Lost permanent
Seasonal
New seasonal
Lost seasonal
Seasonal to perman
Permanent to seaso
Ephemeral permane
Ephemeral seasonal

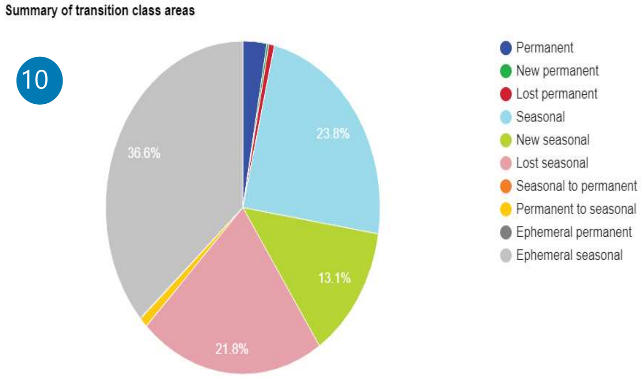

Savandapur
7
6
Urachikottai
Sources: Esri, USGS, NOAA


Summary of transition class areas
7
13.1%
7.2%
24.2%
49.7%
Permanent
New permanent
Lost permanent
Seasonal
New seasonal
Lost seasonal
Permanent to seasonal
Ephemeral permanent
Ephemeral seasonal

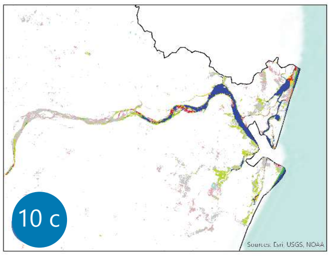

Summary of transition class areas
8
5.7%
43%
13.4%
25.4%
4.7%
7.3%
Permanent
New permanent
Lost permanent
Seasonal
New seasonal
Lost seasonal
Seasonal to permanent
Permanent to seasonal
Ephemeral permanent
Ephemeral seasonal

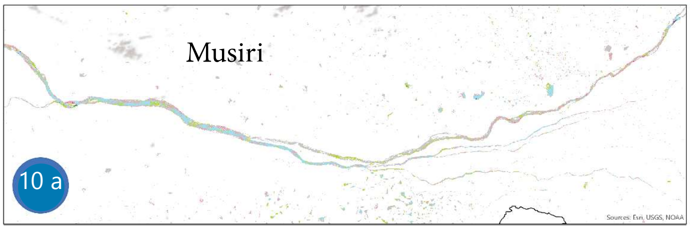

Kodumundi
8
Nalammaranpatti
9
Sources: Esri, USGS, NOAA


Summary of transition class areas
9
9.8%
11.4%
33.6%
45.2%
Permanent
New permanent
Seasonal
New seasonal
Lost seasonal
Permanent to seasonal
Ephemeral seasonal


Summary of transition class areas
10
23.8%
13.1%
21.8%
36.6%
Permanent
New permanent
Lost permanent
Seasonal
New seasonal
Lost seasonal
Seasonal to permanent
Permanent to seasonal
Ephemeral permanent
Ephemeral seasonal


10 b
Sources: Esri, USGS, NOAA


10 c
Sources: Esri, USGS, NOAA


Musiri
10 a
Sources: Esri, USGS, NOAA

A high degree of hydrological alteration was observed during summer months when contribution from baseflow (groundwater) and return flows from agricultural fields was the only source of natural flow in the river. Hydrological alteration reduced with the advent of rainfall in the monsoon season. At most of the gauge stations peak flows were reduced except at Nellithurai gauge station where an abrupt increase in peak flows is recorded by ground observations during monsoon months July and October. This can be caused by release of stored water from Pillur Dam located upstream of this gauge station. Major tributaries of Kaveri in the lower portion of the basin have become completely seasonal or ephemeral in nature while tributaries in the upper part of the basin still have some proportion of permanent water in its reaches. Savandapur sub-basin which is a part of Bhavani basin was declared as closed basin in the mid of 1950s due to expansion of agricultural land which led to over-extraction of groundwater reserve. Inter-basin transfer to neighbouring basin and an increase in drinking water demand have also led to the closure of Savandapur sub-basin. This is evident from prolonged low flow conditions at the gauge station. Nalammaranpati also shows a similar trend with extended periods of low flow or no flow conditions. 45.2% of river section is classified as ephemeral seasonal while 33.6% of river section is identified as lost seasonal,i.e, conversion of seasonal water to land. This indicates terrestrialization of river bed may have occured due to prolonged low flows. Ten dams on the tributaries of Amravathi river may have led to disconnection of tributaries from the main stem of the river in Nalammaranpatti sub-basin reducing flow in the river. Also, overextraction of groundwater for agricultural purposes, as agriculture land is a predominant land cover type in the basin or other consumptive purposes may have also contributed in increasing the hydrological alteration.

Thengumarahada sub-basin is located at a high elevation and is a part of Western Ghats. It has still retained natural vegetation cover due to difficult terrain. A number of hydropower projects are located on the tributaries in this basin which may have impacted the natural flow in the river, but a drastic reduction in low flows and high flows is not observed at the gauge station location. With the advent of monsoon a decrease in hydrological alteration is observed, specially in November month. At Kudige station, a decline in baseflow is observed, while attenuation of peak flows is also evident from the ground observations. Kaveri river originates in Kudige basin and is known to be a perennial river but now the river stretch contains only 16.1% of permanent water, rest is mostly seasonal or epehemeral seasonal. 11.3% of river stretch which was earlier seasonal is now classified as lost seasonal due to extension of aquatic vegetation or agricultutural fields in the river channel specially during low flow conditions. Presence of Harangi dam on a tributary close to Kudige station and over-consumption of groundwater for agriculture and commercial plantations, may have caused alteration in magnitude of monthly flows. During monsoon months, August-September, flow alteration gets reduced possibly due to surface runoff or release of flow from reservoir. A similar trend was observed in T.K. Halli station which has many dams on its sub-tributaries.

Natural variability of river flow is disrupted at gauge station M.H. Halli which is located downstream of Hemavathy dam. A large portion of the river stretch in this basin is seasonal with only 13.1% left as permanent water. This may give a rough estimate of loss of freshwater habitat in a river basin, threatening survival of species existing in the region. K. M. Vadi and T. Narasipur showed a similar trend in alteration of flow regime. Variability in flow regime is severely affected with prolonged low flow or zero flow conditions. Small peak flows are observed during monsoon season. Thus, a high degree of hydrological alteration in magnitude of river flow was observed at nearly all the gauge stations, except TK Halli and Thengumarhada, where flow alteration was relatively lesser.

5.4 Ecosystem Integrity

Ecosystem Integrity is the measure of health of an ecosystem. In order to assess the ecosystem integrity of rivers an indicator framework was developed. This indicator framework was inspired from Freshwater Health Index (FHI) (“Freshwater Health Index,” n.d.) which utilises data from local and global sources to assess the health of riverine ecosystems. Indicators used in this framework are grouped into four main categories, namely, Connectivity Status, Biodiversity, Land-Use and Water Quality.

Connectivity status refers to longitudnal (river channel), lateral (floodplains), temporal (intermittency) and vertical (groundwater and atmosphere), fluvial connectvity in a riverine ecosystem which gets impacted by different pressure factors in a river basin. Three indicators - Degree of Fragmentation, Degree of Regulation and Sediment Trapping Index - from free flowing river dataset (Grill et al., 2019) were adopted for estimating the connectivity status of river segments. River discharge is also impacted by land use in riparian and floodplain areas. Riparian zone which is also seen as a terrestial/aquatic interface play an important role in keeping the rivers healthy. Vegetation in riparian zone stabilizes the river bank by slowing surface runoff and depositing sediments, hence preventing soil erosion. Basin wide land use also impacts surface runoff and groundwater recharge. In order to assess land use and land cover changes in the basin, two indicators, Land Cover Naturalness and Infrastructure development in floodplain areas were adopted from global datasets. Inland water quality is also proposed as a sub-catgeory in the framework. Due to unavailability of data it has not been included in this study. Data from world water quality portal, currently under development by EOMAP can be used in future.

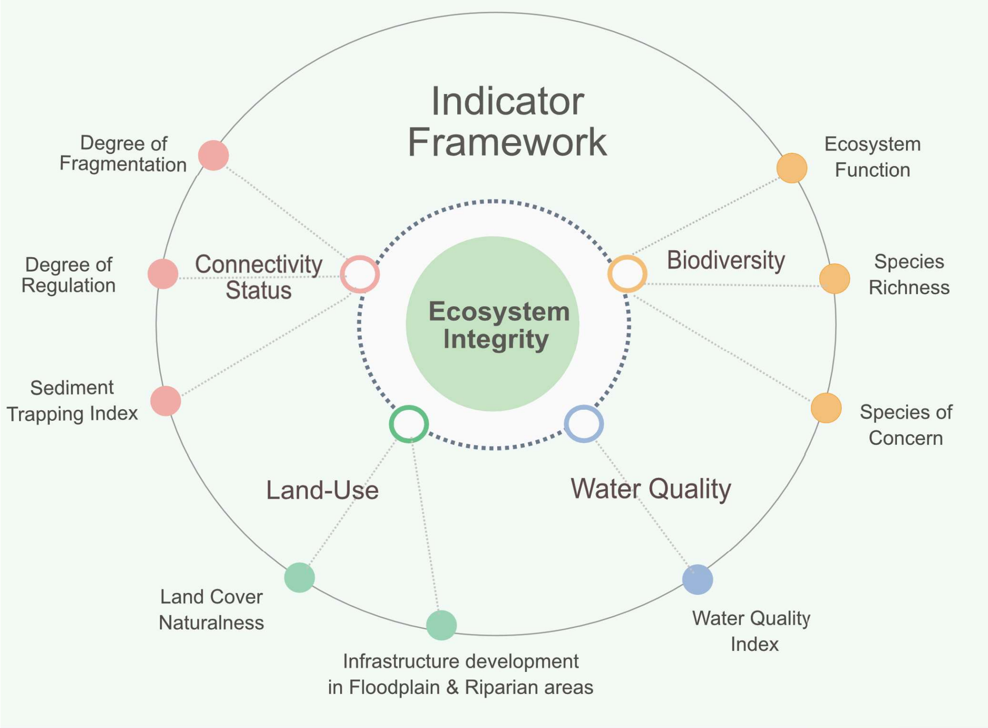


Fig 5.5. Ecosystem Integrity Indicator Framework

Freshwater biodiversity is also incorporated in this framework as the fourth category. Species richness is the count of different species in an ecological community. Species of concern is the number of species in a ecosystem with IUCN red list status as CR (critically endangered), EN (endangered) or VU (vulnerable). Ecosystem function is also proposed as a sub-category for monitoring the health of riparian or floodplain vegetation. Absence of high resolution data for primary productivity or evapotranspiration and encroachment of agricultural lands into riparian and floodplain zone, limits the usage of this variable in the current study.

5.4.1 Degree of Fragmentation

River networks are dendritic or one dimensional in shape, making them more susceptible to effects of habitat fragmentation. Rivers are naturally fragmented by waterfalls, beaver dams or cascades, but anthropogenic factors like damming of river for irrigation, industrial or domestic usage etc., has further divided the rivers into smaller stagnant river reaches. Fragmentation of rivers greatly impacts the ecological community by blocking migration of aquatic species, transport of nutrients, organic matter and sediments. Lack of sediments downstream of a dam causes erosion of river bed and increases chances of flooding downstream. Restricted flow of a river also impacts the water quality and temperature of the river.

In Kaveri river basin around 96 dams have been built, with the oldest one Thonnur dam, built in the year 1000. With expansion of irrigated agriculture a number of dams were built in Kaveri river basin without scientific assessment of the impacts on ecological community. As a result, the main stem of the river and its principal tributaries are highly fragmented (See Fig. 5.6). Kabani river, one of the main tributaries of Kaveri river, has degree of fragmentation in the range of (85-100)% for 63.35% of its length (or 75.87% of its volume). Kabani dam, a major dam on the river, was built in 1974. Since then it has severely altered the surrounding ecosystem. Natural areas were encroached upon, for expanding agriculture downstream and in the periphery of the reservoir. The backwaters of Kabani dam sustains a variety of wildlife in a protected forest reserve, but it has restricted movement of aquatic and terrestial species, making them more vulnerable to other pressures in the region. Similarly, other tributaries of Kaveri river, like Bhavani river (64.04% of length), Shimsha (74.98% of length) and Amravati (55.79% of length), are also highly fragmented due to presence of dams as shown in Fig. 5.6. Fragmentation due to dams or water diversion structures is one of the dominant factor affecting the longitudnal connectivity in the main stem of the river and its major tributaries.

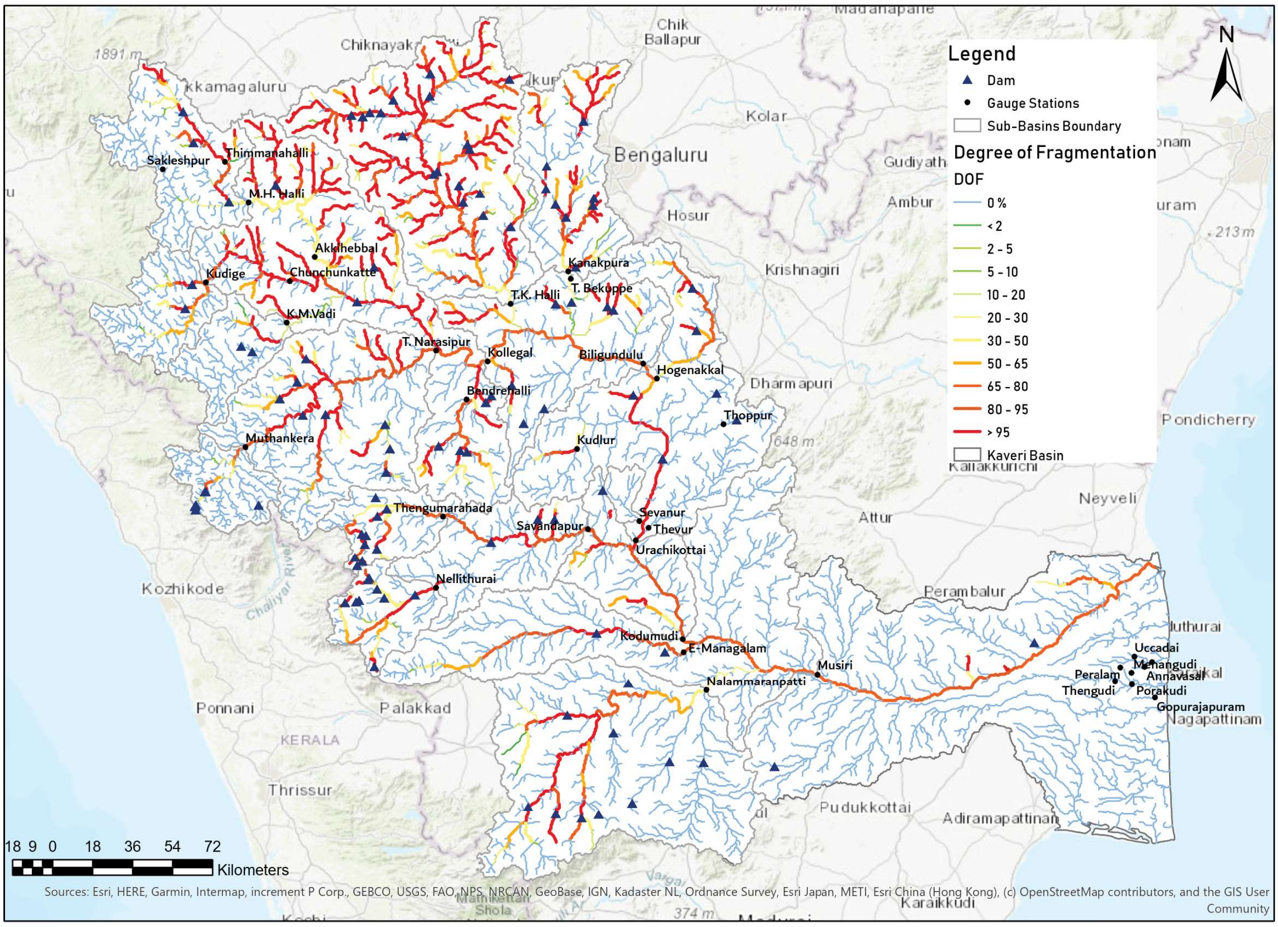


Fig 5.6. Mapping of Degree of Fragmentation in Kaveri river basin. Data - Free Flowing River Dataset

Large dams with low permeability to fishes are negatively impacting riverine populations.
A number of potamodromous fish species are endangered and facing extinction in the Kaveri river basin. The current range of some of these species is shown in Fig 5.7. It can be observed that the population range of many migratory fish species like Tor remadevi, Hypselobarbus micropogon, Tor malabaricus, is restricted by presence of large dams on the river. Tor remadevii, a hump-backed mahseer, is an iconic freshwater fish, native to Kaveri river basin. There is an estimated reduction of 90% in the population range of Tor remadevi and is listed as critically endangered by IUCN.

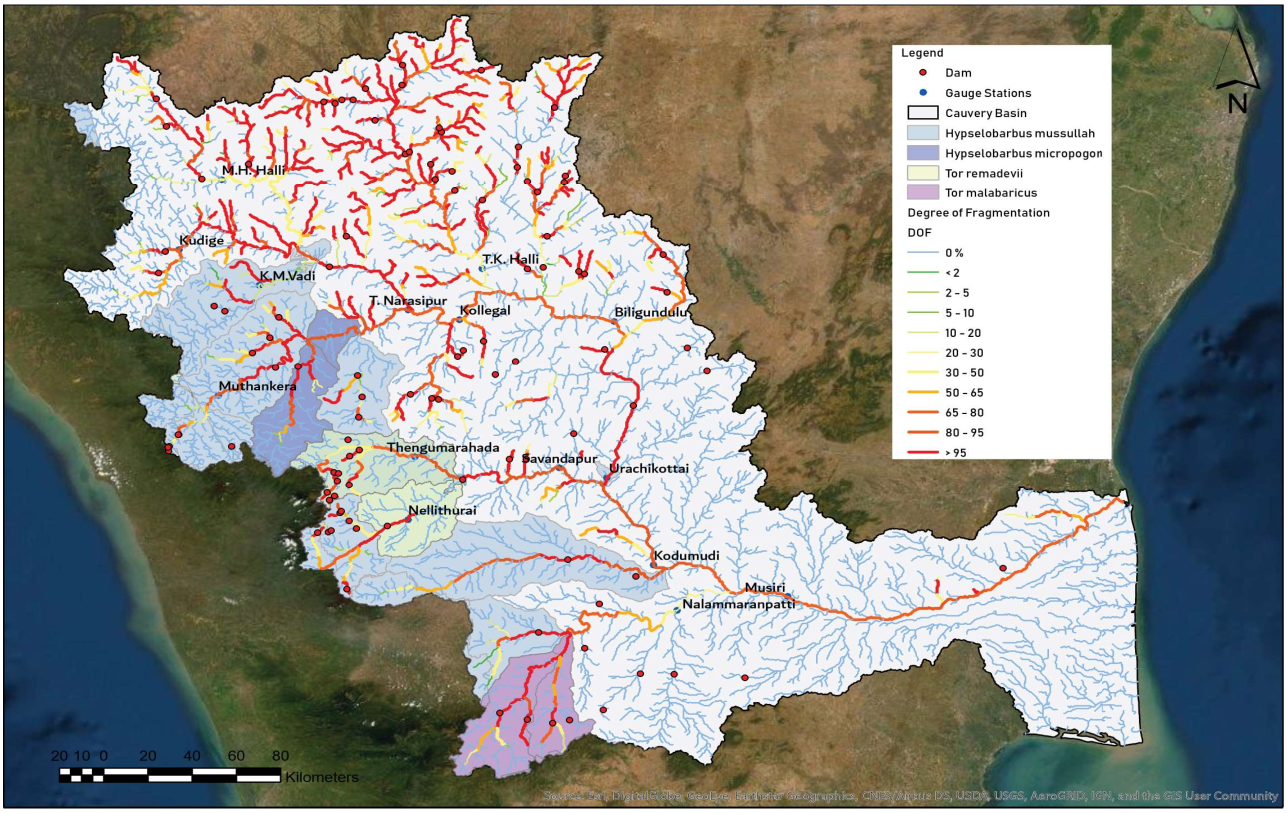


Fig 5.7. Population range of threatened migratory fish determined by IUCN regional assessments in the year of 2010 except for Tor Remadevi which was included in IUCN red list in 2017. Data - IUCN Spatial Data

Small dams on tributaries or sub-tributaries also impacts the freshwater habitats in the long run. It was observed in Kaveri basin, that a number of small dams led to rapid expansion of agriculture in the surrounding region. In summer months, farmers started growing crops and vegetables on the river bed. This led to overuse of groundwater reserve which is a major source of river flow during summer months. Eventually, the tributary lost connection with the main stem of the river. So dams have a cascade effect on the riverine habitat which is difficult to quantify and has not been accounted in the calculation of degree of fragmentation. Hence, in actual the fragmentation effect in Kaveri river basin may be higher than estimated by free flowing river dataset.

5.4.2 Degree of Regulation

Degree of regulation measures the impact of volume of water stored in a dam on the temporal and lateral connectivity of a riverine ecosystem. In Kaveri basin 47.48% of total river volume is impacted by regulated flows from reservoirs. Dams can impact the streamflow characteristics by reducing peak flows and altering low flow and inter-annual flow regime. This is evident from high degree of hydrological alteration from reference natural flow at respective gauge locations. Reservoirs on small rivers with highly variable discharge has high impact on the biological community, as observed in sub-basins Nellithurai and TK Halli where a high prportion of species are threatened.

Reduction in peak flows may also lead to decrease in overbank flooding. In absence of flooding, encroachment of vegetation can occur in the river bed (Fig. 5.8), further decreasing the ground-water reserve. Aquatic organisms can get trapped in these isolated patches and succumb to other pressures like, pollution, temperature change, over-fishing, etc.

Fig. 5.8 Terrestrialization of river bed downstream of a dam in Kaveri basin (Source: ESRI Digital Globe Imagery)

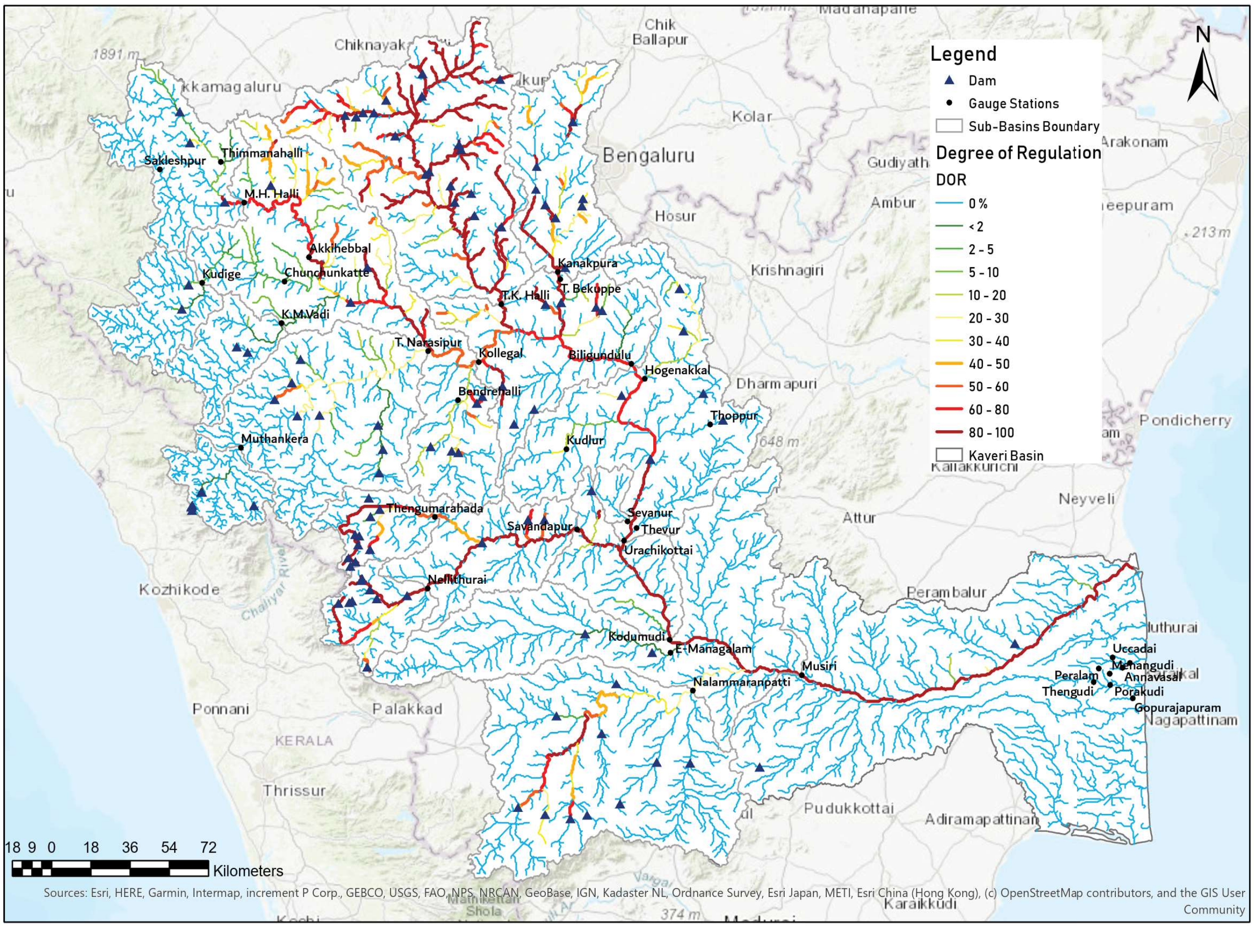


Fig. 5.9 Mapping of Degree of Regulation in Kaveri river basin. Data - Free Flowing River Dataset

Degree of regulation is high in the main stem of the river and also in some major tributaries like Bhavani river , Moyar river (Gauge stations - Savandapur, Thengumarhada, Nellithurai) and Shimsha river (T.K. Halli). Due to the presence of 18 dams on the river network of Shimsha river the entire stretch of Shimsha river is impacted by flow regulation (DOR > 80%). In the case of Bhavani river, 59.87% of its length or 61.76% of river volume has degree of regulation greater than 80%. In some areas of the basin like Kudige , K M Vadi, etc.very low degree of regulation was reported even when a large dam was present upstream of the gauge station. This shows that actual degree of regulation might be higher than reported here. These global datasets should be refined in future by taking more inputs from regional experts or managers.

5.4.3 Sediment Trapping Index

Sediments are trapped by dams on the river systems reducing the transport of sediments to downstream region. This makes the river bed coarser and causes channel erosion and bank instability. Aquatic organisms who make use of sediments for breeding, shelter etc. also suffer with reduced load of sediments from upstream area. Sediment trapping index map for Kaveri river basin overlaps with degree of fragmentation map, as both the pressures originate from dams or reservoirs built across Kaveri river system. The main stem of the river and its principal tributaries have high sediment trapping index. 59.87% length of Bhavani river (Savandapur) and 100% length of Shimsha river (TK Halli basin) have sediment trapping index greater than 80%.

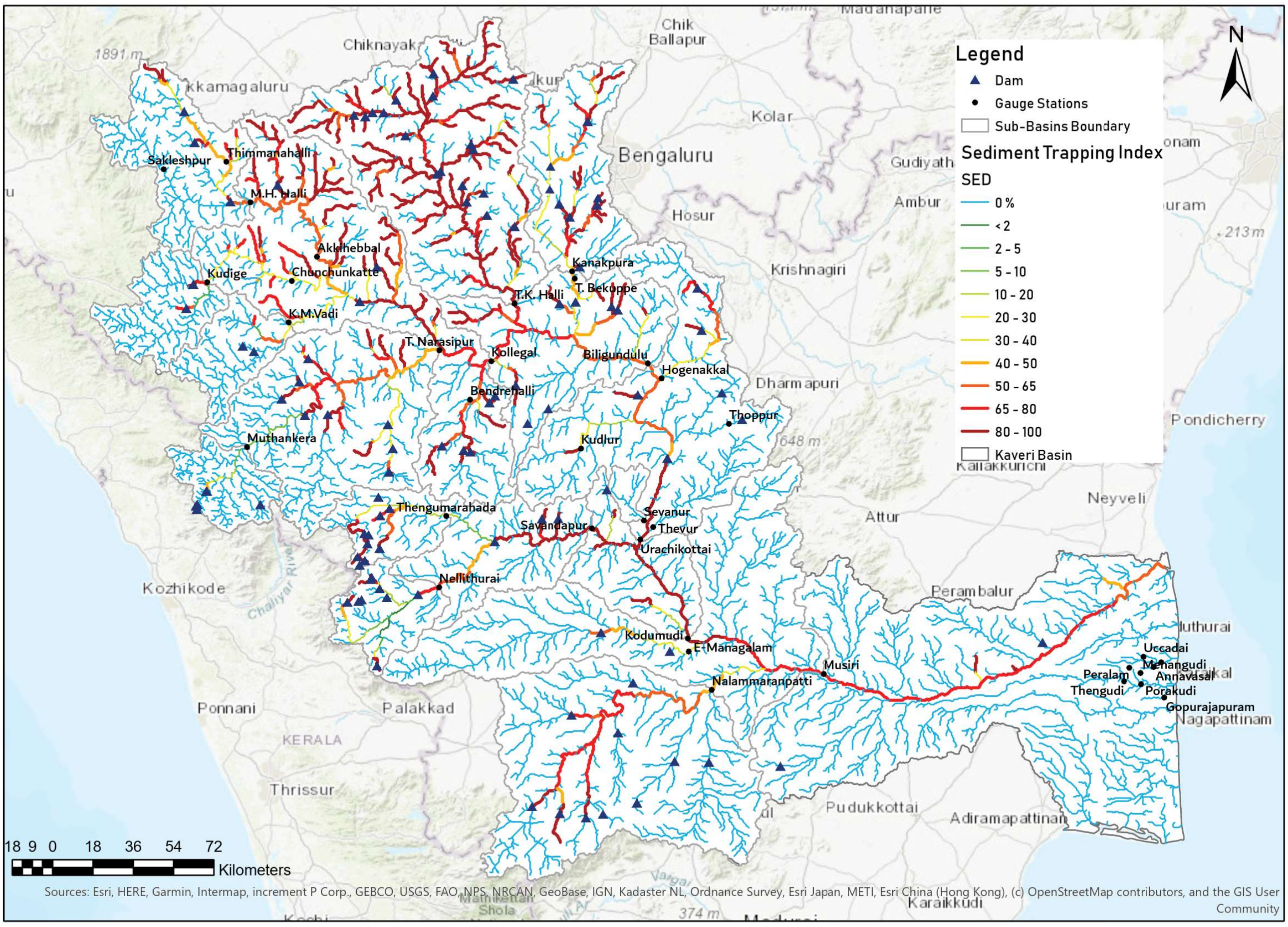


Fig. 5.10 Mapping of Sediment Trapping Index in Kaveri river basin. Data - Free Flowing River Dataset

5.4.4 Land Cover Naturalness

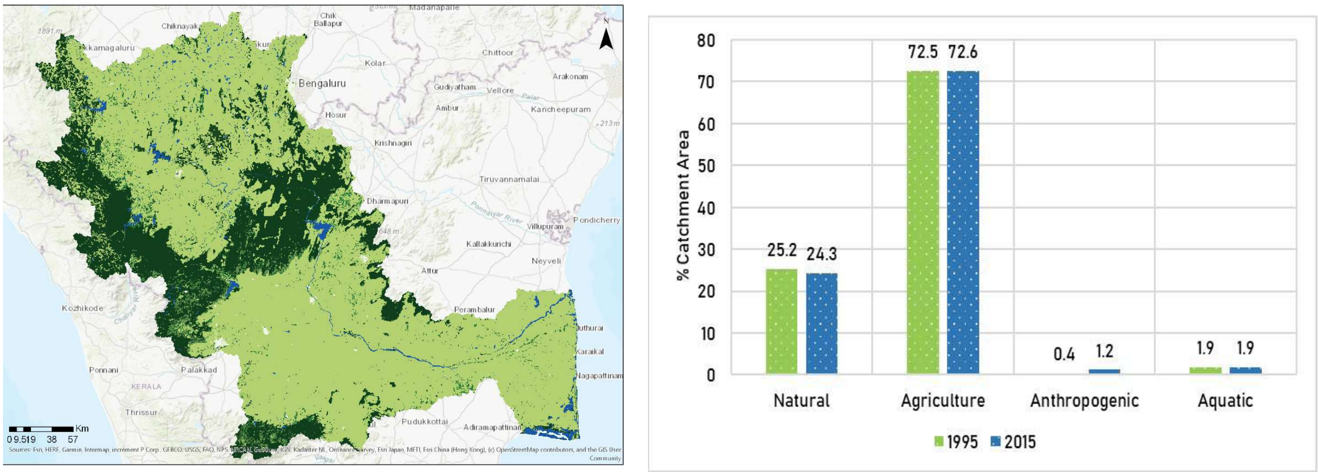
Land cover naturalness depicts the state of land use/land cover in a river basin. Riparian vegetation provides dead organic matter, shade, nutrients, habitat to aquatic species and also plays a key role in regulating water quality of rivers and stabilizing river banks. Encroachment of agricultural lands into riparian or floodplain zone leads to over-extraction of groundwater reserve, causing land subsidence and downcutting of river banks (Fig.5.11). Forest cover in a basin act as sponges due to increased infiltration rates and soil mositure retention. Loss of forest cover can lead to reduction in rooting depth, leaf area aerodynamic roughness, causing decline in evapotranspiration thus affecting streamflow.

Fig. 5.11 Downcutting of river channel possibly due to excessive groundwater pumping & loss of riparian vegetation
(Credit: Sri Harsha Karumanchi)

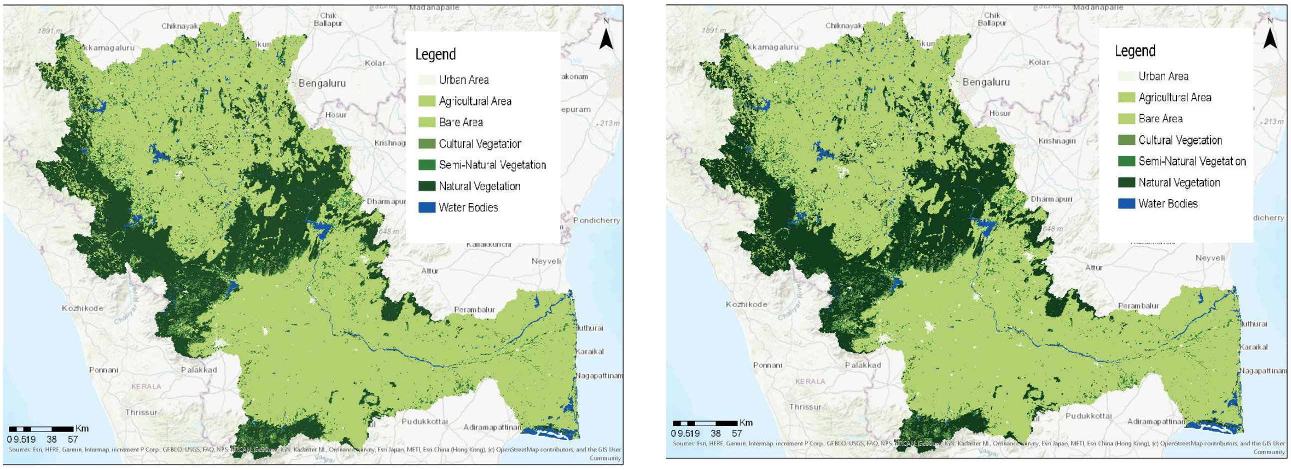
Land cover naturalness index ranges from completely natural to completely modified or urbanized land cover. This indicator was adopted from freshwater health index framework. Land use/land cover types were simplified by assigning weights to each categories according to degree of naturalness (See Appendix 2). As shown in land cover maps for Kaveri basin in Fig.5.12, agriculture is the predominate land use type covering 72.6% of basin area, while natural vegetation covers 24.3% of the total area. Since most of the agricultural expansion occured in 1970s to late 1980s there is no much change in the land cover of the basin during the time period - 1995 to 2015. A slight increase in urban area extent is observed. Riparian vegetation has mostly disappeared from river corridors due to encroachment of agricultural and urban areas.

Most of the sub-basins included in this study have agriculture as the dominant land use type. Though river water is supplied to dry areas for enhancement of irrigated agriculture, most of the farmers rely on groundwater for irrigation as it is more reliable and is freely available. Overuse of groundwater reserves affects the baseflow during summer months, eventually drying up the river. Many perennial streams in Kaveri river basin are becoming seasonal or ephemeral (Fig.5.4) Also, return flows from agricultural lands in river corridors, loaded with pesticides, further pollutes the fragmented river reaches, endangering lives of aquatic species. Wastewater from industries and urban areas also adds to the pollution load in the river. Hence an interplay of many factors leads to decline in freshwater biodiversity and river health. Most of the sub-basins with agriculture as major land use type also have high percentage of threatened species.

Fig. 5.12 Mapping of Land Cover Naturalness in Kaveri river basin from 1995 to 2015 . Data - ESA CCI Land Cover

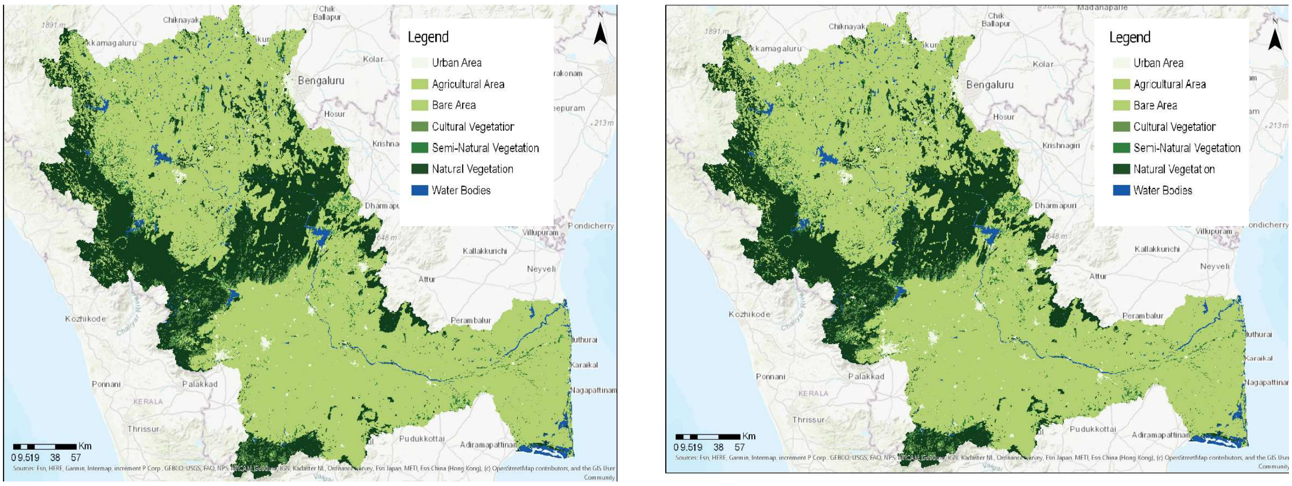


Year - 1995



Year - 2000

Year - 2005



Year - 2010

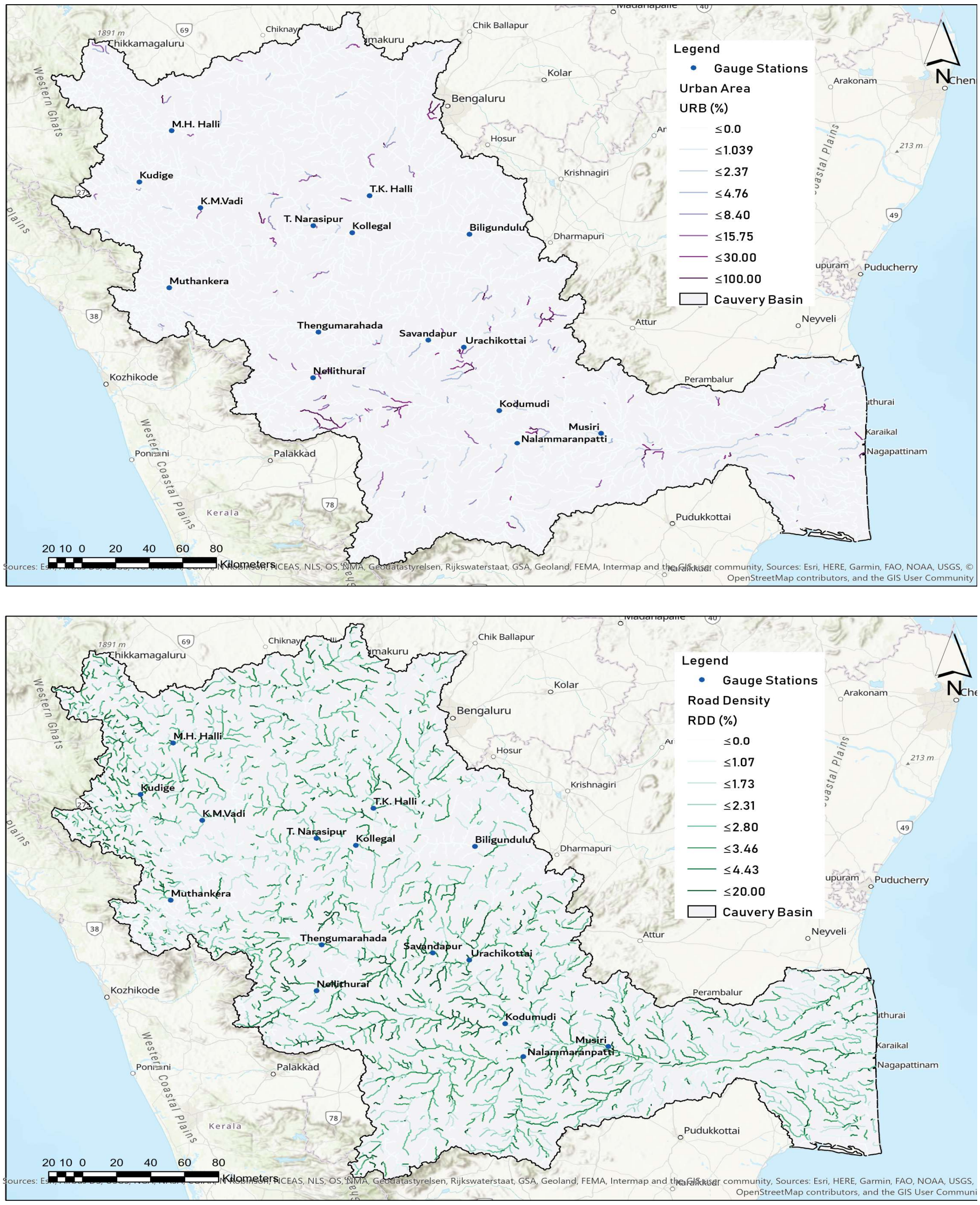
Year - 2015

5.4.5 Infrastructure Development in Floodplain Area

Urbanization (URB) in the floodplain area increases surface runoff due to impervious surfaces and also leads to decline in groundwater recharge. This impacts the lateral connectivity of rivers to floodplain areas. Road density (RDD) is also used as a proxy for estimating loss of lateral and longitudinal connectivity at intersections with streams within 1km buffer area around river reach. In Kaveri basin, the extent of infrastructure development in floodplain area as assessed by free flowing river dataset is not that predominant. c. In sub-basins Musiri, T. Narasipur and Savandapur some extent of urbanization in floodplain area was observed while rest of the sub-basins showed no urbanization. High resolution imagery is required to get an accurate assessment of growth of urban areas in floodplain or riparian regions. Results for road density were consistent throughout the basin with values in the range of 0 to 4.355%. This indicates, the impact of Road Density pressure factor is not that severe in the basin.

Savandapur sub-basin has the highest value of 4.355 for Road Density index.

Fig. 5.13 Mapping of Urban Area (URB) (top) and Road Density (RDD) (bottom) in Kaveri Basin . Data - Free Flowing River Dataset



Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

5.4.6 Freshwater Biodiversity

Kaveri river basin comprises of seven ecoregions (Fig.5.14), Western Ghats (with moist deciduous forest and montane forest), Deccan Plateau (with semi-evergreen moist forests & thorn scrub forest) and Bay of Bengal Mangrove. Rich forests of Western Ghats are considered as hotspots of India's biodiversity. The moist decidous forests of western ghats harbor many endemic species and act as riparian corridors, providing habitat to many terrestial and aquatic species. Kaveri delta, is the most fertile region in the basin and is very rich in biodiversity with 72% of total fish species existing in the estuarine zone. Six freshwater taxonomic groups : fishes, molluscs, odonata, shrimps, plants and crabs are chosen as representatives of the freshwater biome and are discussed below. Species richness maps for all the taxonomic groups were developed using spatial data for species from IUCN.

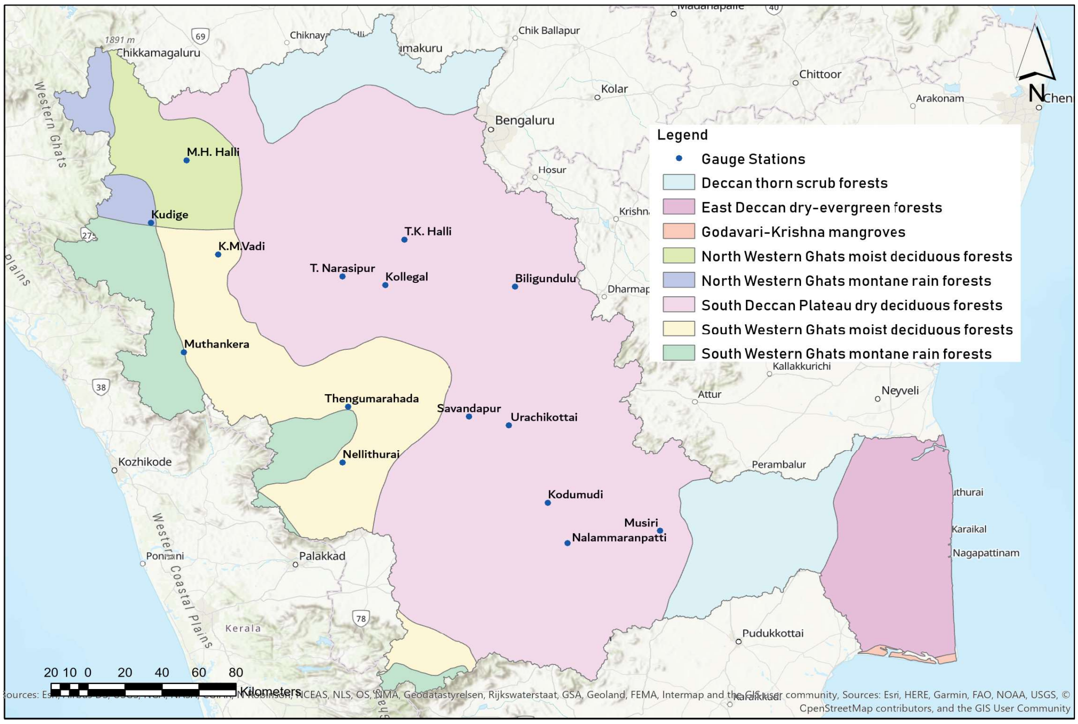


Fig. 5.14 Mapping of Ecoregions in Kaveri basin.
Ecoregions are ecosystems of regional extent.

Data - Ecoregions2017

Odonatas are often used as bio-indicators for monitoring health of riverine ecosystems. Adult dragonflies and demselflies depend upon terrestial habitats while their larvae develop in aquatic environment. High richness of odonata species is found in forested upper catchments of Kaveri basin, than lower catchments where agriculture is the dominant land use type. These species play a critical role in regulating water quality, cycling of nutrients and maintenance of habitat structure. A total of 64 genera belonging to 14 distinct families of odonatas are found in the Kaveri basin. 3.4% of genera endemic to this region is listed under threatened category. Agricultural expansion in riparian areas make these species susceptible to a number of threats like, pesticide pollution, sediment runoff and drying of rivers during summer months. In a study it was found that endemic fauna was totally absent from streams flowing through coffee plantations (Molur, Smith, Daniel, & Darwall, 2010).

Kaveri river basin is also home to large variety of freshwater plants, 164 genera of freshwater plants belonging to 47 families are found in the basin, out of which 6.6% of genera is counted in the category of threatened species. Habitats of aquatic plants are getting severely impacted by pollution from agricultural lands, industrial & urban sewage. Mining around freshwater habitats, sand mining and conversion for non-agricultural usage, increase in land used for grazing, as well as large scale plantations of commercial crops like coffee, rubber, tea etc., has also led to a decline in availability of suitable habitats for aquatic plants endemic to the basin.

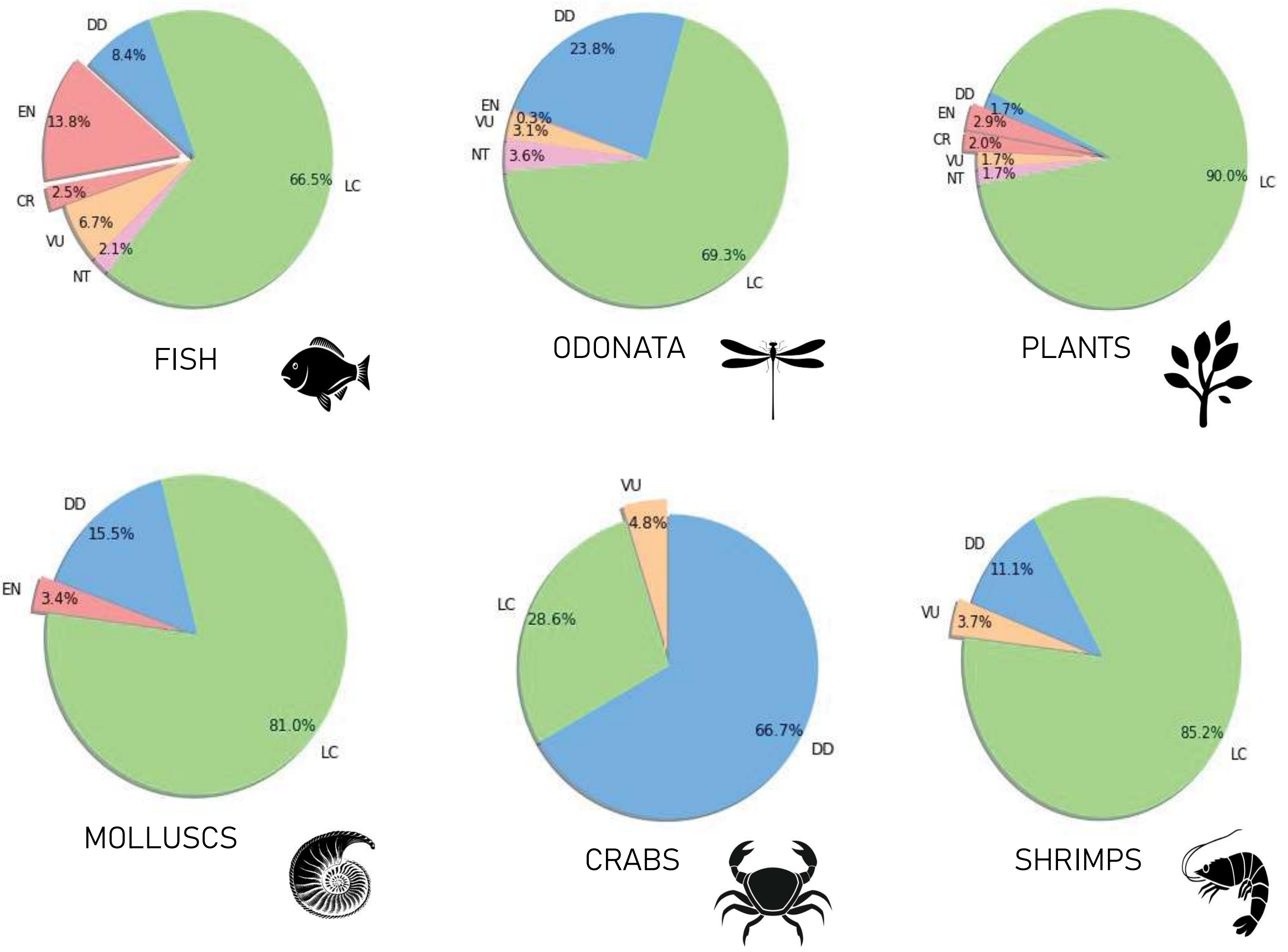


Fig. 5.15 Proportion of freshwater species (Fish, Odonata, Plants, Molluscs, Crabs & Shrimps) in IUCN red list category in Kaveri basin
Data - IUCN Red List

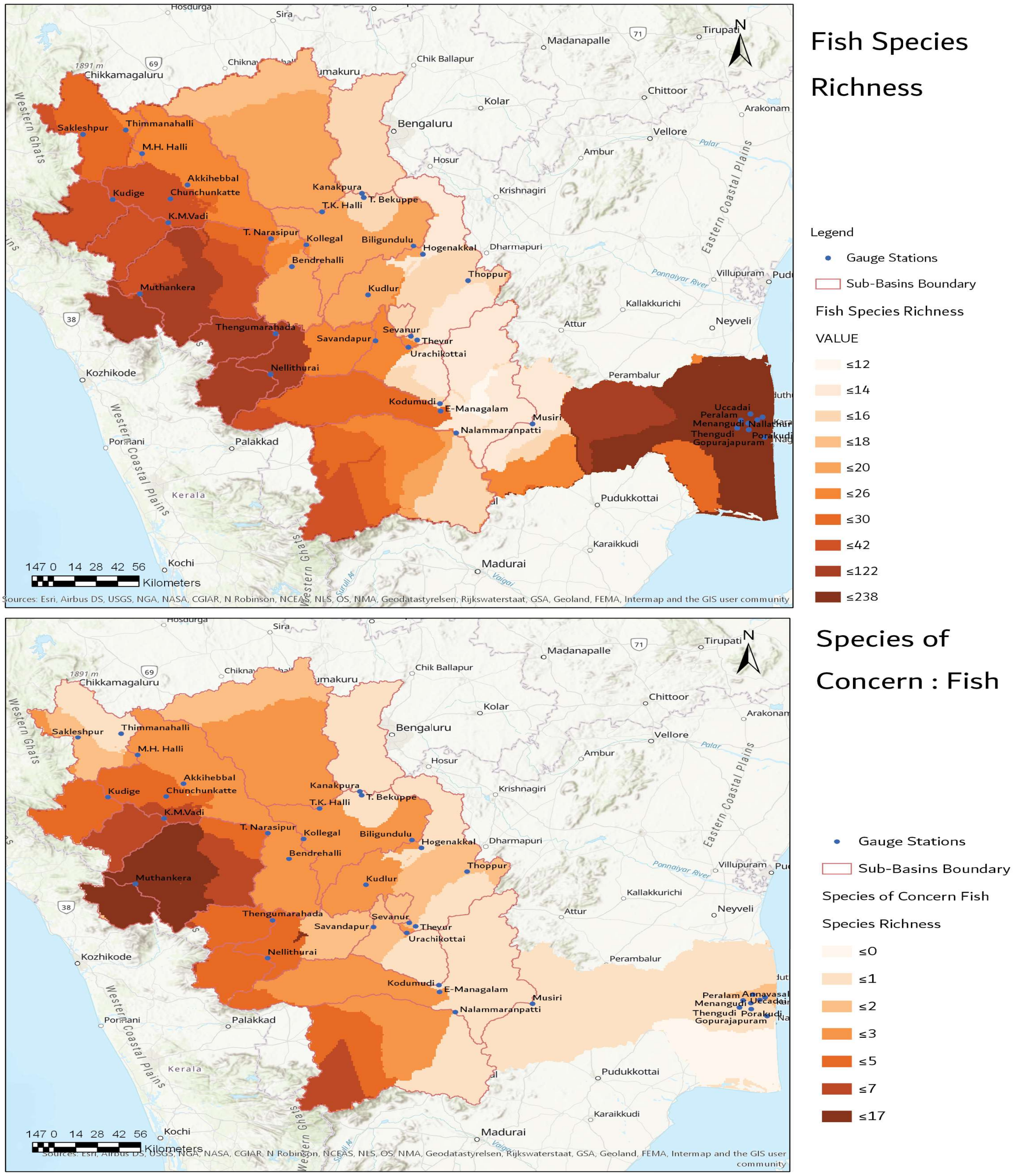
Molluscs play an important role in ecosystem functioning. 37 genera of freshwater molluscs belonging to 10 different families are endemic to Kaveri river basin. Pseudomulleria dalyii is an endangered species found in Western Ghats is now restricted to only five locations, with a total extent of 5000 km2. (Molur, Smith, Daniel, & Darwall, 2010) Three species of Cremnoconchus genus (family : littorinidae) are also listed as threatened species. They are very habitat specific and thrive in the spray zone of perennial waterfalls in Western Ghats. Habitat destruction due to construction of dams, water diversion structures, pollution, sand mining and invasive species of aquatic plants thriving in lentic environment are some of the major threats affecting freshwater molluscs in the region.

Freshwater crabs belonging to genera , Oziothelphusa, Barythelphusa, Baratha, Vanni, Vela, Lamella, Snaha, Inglethelphusa, Travancoriana, Gubernatoriana and Spiralothelphusa are endemic to Kaveri river basin. Among 11 genera of gecarcinucidae crabs, 2 species of Oziothelphusa genus are listed as vulnerable. Crabs usually live in lentic or lotic habitats, like rivers, lakes, etc. They are found near macrobenthos or aquatic vegetation and are adpated to semi-terrestial mode of life. Shrimps are only found in aquatic environment. Three genera of shrimps belonging to family Palaemonidae (genus : Macrobrachium, Leptocarpus) and Atyidae (genus : Caridina) are found in the basin. Macrobrachium gurudeve is the vulnerable species of shrimp which is noww restricted to a single location, i.e., Bhavani river. Several species of Gecarcinucidae crabs are point endemics and are highly impacted by pesticides pollution from agricultural lands as well as wastewater from industries and urban areas. Drying out of river beds due to damming of rivers severely affects the population of freshwater crustaceans. Mass mortality of juvenile Macrobrachium trapped in oxygen depleted, warm puddles of Kaveri river was reported by Mariappan and Balasundaram (1999). Overfishing during breeding season is another major threat to crustaceans population in Kaveri river basin.

Fifty six families of freshwater fishes with 146 genera exist in Kaveri basin. High fish species richness (122-218 species per catchment) is found in upper catchments of kaveri river basin located in south-western ghats and also in the delta region. There is a decline in species richness of fishes in eastern part of the basin, classified as deccan plateau ecoregion. Distribution of threatened species (Fig.5.15) is consistent with species richness distribution map, with an exception of delta region. A high number of threatened species are concentrated in the south-western ghats, where presence of large number of endemic fish species is recorded.A number of factors, like deforestation, invasive species, alteration of drainage basin condition, fragmentation & regulation of rivers, over-extraction of groundwater, pollution as well as climate change impact the freshwater fish species in the basin.

Species richness maps of freshwater Molluscs, Crabs, Shrimps, Plants and Odonata in Kaveri river basin are included in Appendix 3.

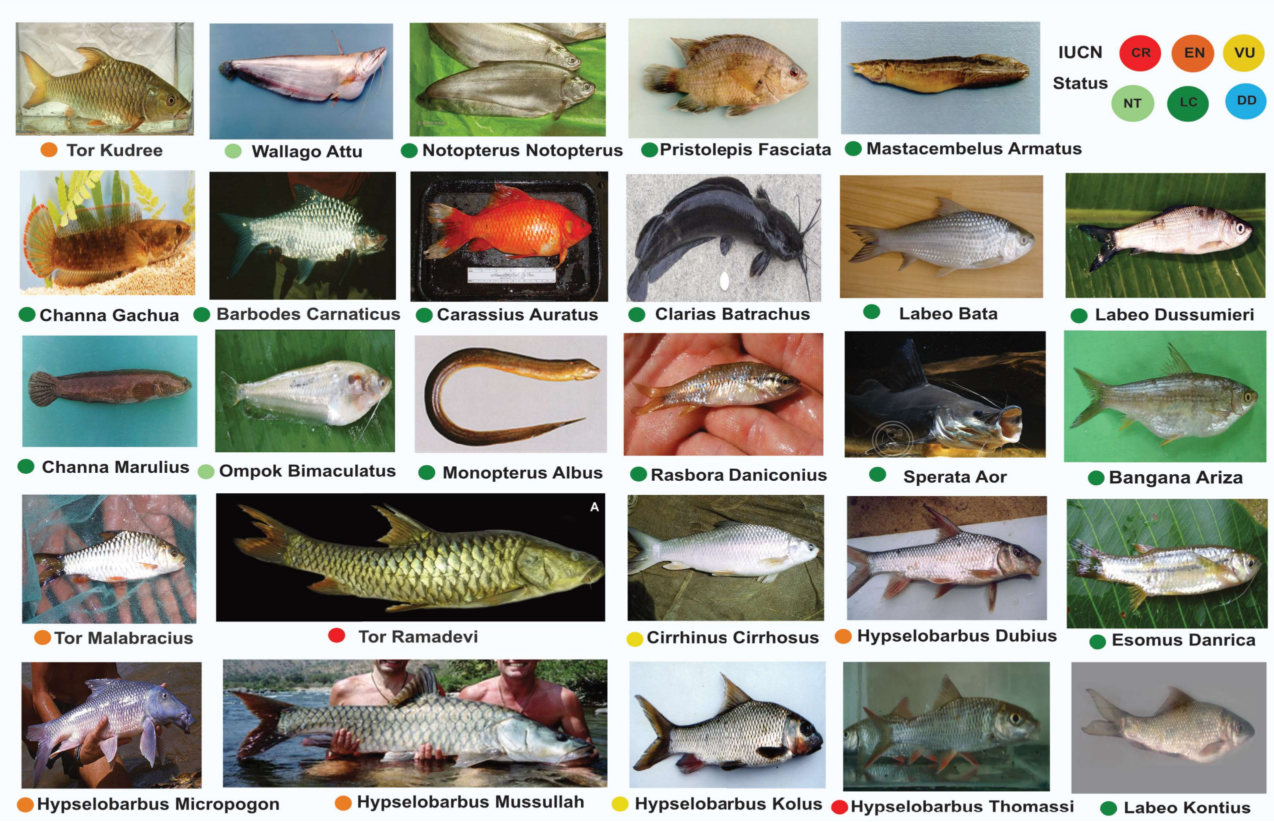
Fig. 5.16 Mapping of freshwater fish species richness and species of concern (IUCN Red List category : CR, EN & VU) richness in Kaveri basin. Data - IUCN Red List

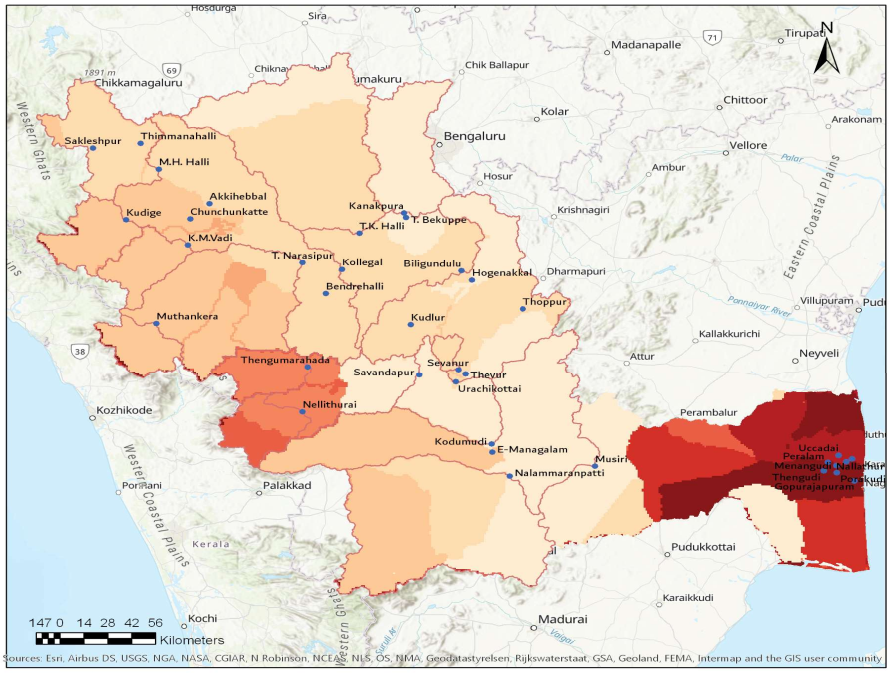


Migratory Fishes of Kaveri Basin

Around 96 genera of migratory fishes are found in the river networks of Kaveri basin. These fishes exhibit different migratory movements during their lifetime, according to their preference of freshwater habitats. Some fishes migrates within freshwater only (Potamodromous) while others move from sea up the river to spawn (Anadromous) or from freshwater to seawater to spawn (Catadromous). Kaveri basin is home to 27 potamodromous, 9 catadromous, 45 amphidromous, 11 anadromous and 4 oceanodromous fishes (See Appendix 3). Among all the categories, potamodromous fishes are most affected by degradation of freshwater habiats with 9 of them listed as threatened species. Tor Remadevi and Hypselobarbus Thomassi are two endemic potamodromous species which are critically endangered.

Fig. 5.17 Potamodromous migratory fishes in Kaveri basin alongwith their Red List category status (top)
Mapping of Potamodromous fish species richness in Kaveri basin (bottom)
Data - Fish Base & IUCN Red List





Potadromous Fish Species Richness

Legend
- ● Gauge Stations
- ▭ Sub-Basins Boundary

Potadromous Fish Species Richness
Value
- ≤0
- ≤2
- ≤3
- ≤4
- ≤6
- ≤7
- ≤11
- ≤12
- ≤13
- ≤18

5.5 Ecosystem Integrity of Sub-Basins of Kaveri

Ecosystem integrity of sub-basins of Kaveri river was assessed based on the three major indicators, connectivity status, land use and biodiversity. Data from global datasets were utilised and presented at sub-basin scale in order to assess the variation in indicators from one part of the basin to another. Results for all the indicators is presented in Table 10 . All the sub-basins are grouped according to respective river classes.

Table 10 - Results of ecosystem integrity indicators for 14 sub-basins of Kaveri basin.

Gauge Stations	Connectivity	Land Use		Water Use	Hydrological Alteration	Ecological Importance	
		Infrastructure	Land Cover Naturalness			Species Richness (Fish)	Species of Concern (Fish)
T. K. Halli	DOF - 24.7 DOR - 100 SED - 82.1	URB - 0 RDD - 2.68	*SB - 30 **FP - 30	14.9	0.44	SR - 20 % SR - 4.17	SC - 3 % SC - 15
Nellithurai	DOF - 98.11 DOR - 100 SED - 65.61	URB - 0 RDD - 2.33	SB - 100 FP - 100	19.6	4.69	SR - 70 % SR - 14.6	SC - 5 % SC - 7.14
K. M. Vadi	DOF - 12.14 DOR - 0.41 SED - 20.14	URB - 0 RDD - 0.98	SB - 70 FP - 30	4	6.55	SR - 36 % SR - 7.5	SC - 6 %SC - 16.67
Kollegal	DOF - 68.64 DOR - 58.50 SED - 69.66	URB - 0 RDD - 0	SB - 30 FP - 30	42.7	4.33	SR - 24 % SR - 5	SC - 3 % SC - 12.5
Biligundulu	DOF - 66.24 DOR - 64.73 SED - 57.41	URB - 0 RDD - 0	SB - 100 FP - 50	56.9	4.51	SR - 20 % SR - 4.17	SC - 3 % SC - 15
Urachikottai	DOF - 97.83 DOR - 98.88 SED - 88.98	URB - 28.13 RDD - 3.22	SB - 70 FP - 30	69.9	5.68	SR - 16 % SR - 3.33	SC - 2 % SC - 12.5
Kodumudi	DOF - 87.14 DOR - 100 SED - 85.31	URB - 0 RDD - 1.55	SB - 30 FP - 30	68.8	3.11	SR - 16 % SR - 3.33	SC - 1 % SC - 6.25
Musiri	DOF - 73.99 DOR - 85.23 SED - 71.52	URB - 2.37 RDD - 3.25	SB - 30 FP - 30	65.9	2.79	SR - 14 % SR - 2.92	SC - 1 % SC - 7.14
Thengumarahada	DOF - 77.35 DOR - 54.39 SED - 13.39	URB - 0 RDD - 3.82	SB - 100 FP - 60	6.3	1.36	SR - 62 % SR - 12.92	SC - 4 % SC - 6.45
Savandapur	DOF -91.35 DOR - 100 SED - 83.75	URB - 3.12 RDD - 4.35	SB - 30 FP - 30	15.5	2.69	SR - 22 % SR - 4.58	SC - 2 % SC - 9.09
Nalammaranpatti	DOF - 27.27 DOR - 21.33 SED - 40.21	URB - 0 RDD - 0.92	SB - 30 FP - 30	87.9	1.27	SR - 22 % SR - 4.58	SC - 3 % SC - 13.64
Kudige	DOF - 90.87 DOR - 2.38 SED - 24.82	URB - 0 RDD - 4.28	SB - 100 FP - 60	0.5	4.33	SR - 40 % SR - 8.33	SC - 5 % SC - 12.5
M. H. Halli	DOF - 47.39 DOR - 70.53 SED - 55.37	URB - 0 RDD- 1.64	SB - 30 FP - 30	9.4	2.231	SR - 28 % SR - 5.8	SC - 1 %SC - 3.57
T. Narasipur	DOF - 87.90 DOR - 26.17 SED - 44.74	URB -0.74 RDD - 1.22	SB - 30 FP - 30	14.3	5.86	SR - 42 % SR - 8.75	SC - 8 % SC - 19.05

⬜	very hot, low moisture region, very small river, medium & high stream power	🟫	very hot, low moisture region, small river, low stream power
🟪	very hot, low moisture; high elevation region, very small river, medium & high stream power	🟦	very hot, high elevation region, small river, medium & high stream power
🟩	very hot, low moisture region, medium river, medium & high stream power	🟨	very hot, high to low moisture region, small river, medium & high stream power

*SB - Sub-basin
**FP - Floodplain

5.6 Environment Management Class (EMC)

Environment management classes, represent current or desired ecological condition of a river. Indicators used for estimating the ecosystem integrity of a river basin can be organized into 6 classes,with declining ecological condition of a river from A (natural) to D (critically modified). This classification system can be instrumental in deciding priority actions for restoration of a river. Stakeholders can easily understand the trade offs between flow alteration and ecological condition of a river through these scenarios. Currently, indicators defined on a common scale of (0 to 100%) are included in the EMC framework. Hydrological alteration and ecological importance of a river basin in terms of species richness or species of concern should also be included in the framework. Also, a preliminary assessment of ecosystem services derived from a river like water use/supply, water quality regulation, sediment regulation, cultural importance, flood regulation, biomass for consumption, can also be included in the given framework, to understand the trade-offs between ecosystem services and ecological condition of a river. Thresholds for classes A to D can be based upon flow alteration-ecological response relationship. Here, threshold values for all the indicators have been decided arbitrarily.

Table 11- Framework for Environment Mangement Classes

Class	Ecological Condition	Connectivity (%)	Land Use (%)		
		(DOF. DOR. SED)	URB	RDD	LCN
A	Natural rivers with minor modification of in-stream and riparian habitat	(0-10)	(0-10)	(0-10)	(80-100)
B	Slightly modified and/or ecologically important rivers with largely intact biodiversity and habitats despite water resources development and or/ basin modification	(10-20)	(10-20)	(10-20)	(80-60)
C	Habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact, some sensitive species are lost and or reduced in extent; alien species present	(20-40)	(20-40)	(20-40)	(60-40)
D	Large changes in natural habitat, biota, and basic ecosystem functions have occured, species richness is clearly lower than expected, much lower presence of intolerant species, alien species prevail.	(40-60)	(40-60)	(40-60)	(40-20)
E	Habitat diversity and availability have declined, species richness is strikingly lower than expected, only tolerant species remain, indigenous species can no longer remain, alien species have invaded the ecosystem	(60-80)	(60-80)	(60-80)	(20-10)
F	Modifications have reached a critical level, ecosystem has been completely modified with almost total loss of natural habitat and biota, in the worst case basic ecosystem functions have destroyed and changes are irreversible	(80-100)	(80-100)	(80-100)	(10-0)

In a recent study (Grizzetti et al., 2019), it was found that higher delivery of ecosystem services from riverine ecosystems is mostly correlated with better ecological condition. Understanding links between pressures, ecological condition and ecosystem services can be instrumental in deciding environment flow requirements and promote sustainable management of water resources.

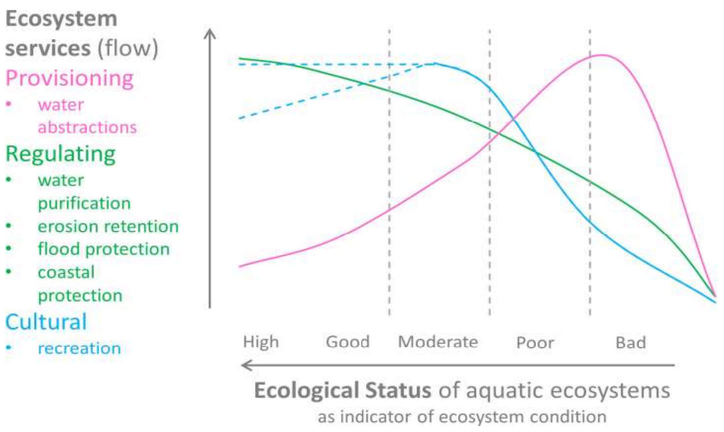
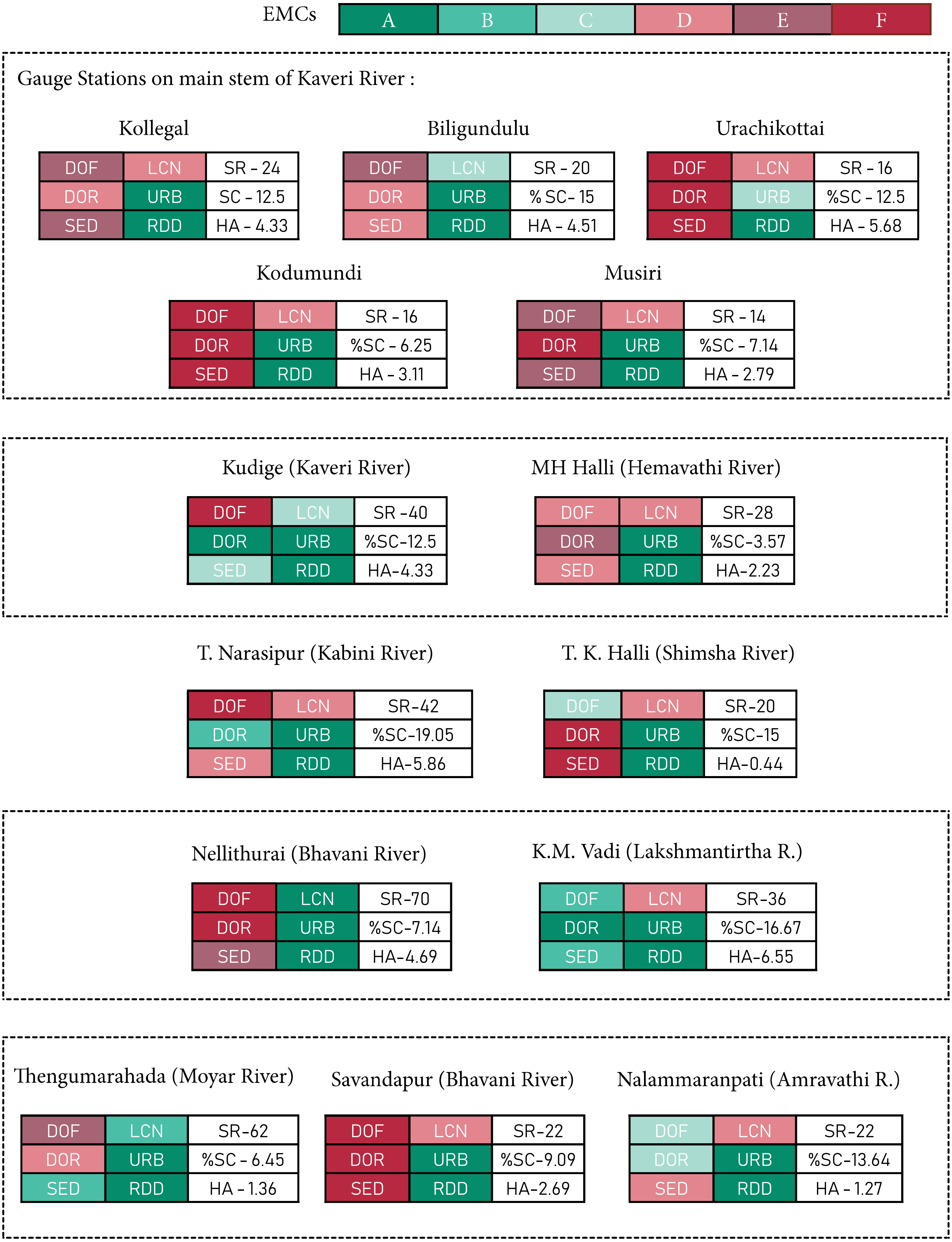


Fig. 5.18 Conceptual Relationship between Ecosystem Services & Ecosystem Condition (Source : (Grizzetti et al., 2019))

5.7 Summary of Ecosystem Integrity & Hydrological Alteration of Sub-Basins of Kaveri River

Fig. 5.19 Summary of Ecosystem Integrity and Hydrological Alteration in Sub-basins of kaveri
Note : For LCN index, median value of LCN in the Floodplain region is considered here.



EMCs					
A	B	C	D	E	F

Gauge Stations on main stem of Kaveri River :

Kollegal

DOF	LCN	SR - 24
DOR	URB	SC - 12.5
SED	RDD	HA - 4.33

Biligundulu

DOF	LCN	SR - 20
DOR	URB	% SC - 15
SED	RDD	HA - 4.51

Urachikottai

DOF	LCN	SR - 16
DOR	URB	%SC - 12.5
SED	RDD	HA - 5.68

Kodumundi

DOF	LCN	SR - 16
DOR	URB	%SC - 6.25
SED	RDD	HA - 3.11

Musiri

DOF	LCN	SR - 14
DOR	URB	%SC - 7.14
SED	RDD	HA - 2.79

Kudige (Kaveri River)

DOF	LCN	SR -40
DOR	URB	%SC-12.5
SED	RDD	HA-4.33

MH Halli (Hemavathi River)

DOF	LCN	SR-28
DOR	URB	%SC-3.57
SED	RDD	HA-2.23

T. Narasipur (Kabini River)

DOF	LCN	SR-42
DOR	URB	%SC-19.05
SED	RDD	HA-5.86

T. K. Halli (Shimsha River)

DOF	LCN	SR-20
DOR	URB	%SC-15
SED	RDD	HA-0.44

Nellithurai (Bhavani River)

DOF	LCN	SR-70
DOR	URB	%SC-7.14
SED	RDD	HA-4.69

K.M. Vadi (Lakshmantirtha R.)

DOF	LCN	SR-36
DOR	URB	%SC-16.67
SED	RDD	HA-6.55

Thengumarahada (Moyar River)

DOF	LCN	SR-62
DOR	URB	%SC - 6.45
SED	RDD	HA - 1.36

Savandapur (Bhavani River)

DOF	LCN	SR-22
DOR	URB	%SC-9.09
SED	RDD	HA-2.69

Nalammaranpati (Amravathi R.)

DOF	LCN	SR-22
DOR	URB	%SC-13.64
SED	RDD	HA - 1.27

Summary for Kaveri River :

Kaveri river originates from sub-basin Kudige, where the main stem of the river has high degree of fragmentation due to the presence of two reservoirs (Harangi & Chiklihole) on its tributaries. Degree of regulation is in the safe range. Thus, in Kudige basin longitudnal connectivity is highly affected while lateral and temporal connectivity is in safe range. This is also evident from moderate hydrological alteration observed at the gauge station. Alteration in magnitude of river flow is getting reduced after the monsoon months, as high amount of rainfall (600 mm approximately) is received by the basin. It is also home to 40 genera of fishes, out of which 5 are assessed as threatened. A high percentage of threatened fish species, can be because of pesticide pollution from coffee plantations (Molur, Smith, Daniel, & Darwall, 2010). Also, it was reported in a study that coffee was initially grown in agroforestrs. But with increasing fluctuations in climate, farmers started using exotic shade trees like australian silver oak trees instead of native ones. Agroforests with exotic trees had lower soil carbon due to lower litter quality. This reduced the microbial activity, hence porosity of soil was impacted, leading to decline in groundwater recharge (Nesper, Kueffer, Krishnan, Kushalappa, & Ghazoul, 2017).

All the gauge stations on the main stem of river Kaveri, Kollegal, Biligundulu, Urachikottai, Kodumundi, and Musiri, have high degree of fragmentation (DOF), regulation (DOR) and sediment trapping index (SED) and the index value increases, downstream of the basin. Between Kollegal and Biligundulu no major dam is present, still both the stations have nearly equal degree of fragmentation, this might be due to decreased inflows from tributaries, Shimsha & Arkavathy which are highly fragmented as well. Downstream of Biligundulu station Kaveri river drops and creates waterfalls (Hogenakkal), and then turns in south direction to enter Tamil Nadu where the flow is restricted by one of the largest dam in the state, Mettur dam.

At Urachikottai, which is located downstream of Mettur dam, the pressure factors, DOF, DOR, SED, jump from class E to class F, indicating river reach is critically modified. This is also evident from 12.5% of threatened species occuring in this sub-basin. Agricultural land expanded downstream of the dam, hence there is an additional pressure of overextraction of groundwater on the natural flow of the river. Degree of fragmentation might be higher than estimated here due to over use of groundwater reserve for agriculture. Moreover, in this sub-basin a significant extent of urbanization in floodplain area is also assessed. This may further reduce groundwater recharge. As the river progresses further south and reaches Kodumundi, there is still no change in the pressure factors, river stretch is still in a critical condition. Bhavani river (GS-Savandapur) which joins Kaveri river at Kodumundi is already over-allocated. Bhavani basin was declared as a closed long back in 1950s. Losing connection with one of its principal tributary, severely impacts Kaveri river as inferred from ecosystem integrity indicators at Kodumundi.

Finally, river enters delta region passing through Musiri gauge station. A slight improvement in DOF and SED is observed but DOR still remains in class E. Inflow from Amravathy river (Nalammarapati) may have reduced the fragmentation effect. DOR still remains high as a number of water diversion structures are present between Kodumundi to Musiri gauge station and also further ahead in the delta region. In addition to this extensive paddy cultivation is practised in this region, with farmers sowing three crops in a year, which lowers the groundwater levels as most of the farmers in India use groundwater for irrigation.

Hence, a number of stressors, river fragmentation, flow regulation, over-extraction of groundwater, trapping of sediments by dams are affecting the freshwater habitats in Kaveri river. DOF is currently assessed as a dominant pressure but impact of groundwater extraction on river flow is still uncertain. A number of other stressors, water quality, temperature, sand mining have not been taken into account but can severely impact river network specially when natural flow is reduced significantly.

Summary for Tributaries:

MH Halli gauge station is located downstream of a major dam on Hemavathy river, which is impacting the longitudnal, lateral and temporal connectivity of the main stem of the river. A high value for degree of fragmentation, regulation and sediment trapping index is observed in this sub-basin. Flow regime is also impacted by two other dams located on its tributaries. Peak flows during the monsoon season have been stabilised by dams. There is also a reduction in baseflow, possibly, due to overuse of groundwater for agriculture. This basin is rich in biodiversity and only one fish genus is assessed as threatened.

KM Vadi sub-basin is located at a high elevation area and has many small dams on its sub-tributaries. Most of these small dams are not considered in the analysis of free flowing river dataset because which connectivity status indicators have very low value. Also, some of the tributaries in this basin, which were dammed long ago between 1960s-1970s have now lost connection to the main river as agriculture expanded rapidly along the periphery of the river and as well as on the river bed. Thus dams have a cascading effect on the connectivity of a river. A very high percentage of threatened species occur in this basin. Potamodromous migratory species is one of them (Fig.5.7). A detailed assessment of this basin is required to identify the pressures on aquatic organisms.

T.Narasipur located on Kabini river, has high degree of alteration. There are many dams on the tributaries as well as on the main stem of the river due to which degree of fragmentation in very high in this basin. Agriculture is the dominant land cover type in the floodplain region indicating over-use of groundwater & pollution from farms located very near to the river. A very high percentage of threatened species is recorded in this sub-basin, some of them are migratory and are also point endemic to this region as it comes under Western Ghats. This basin should also be assessed further as many endemic fish species belonging to Hypselobarbus genus are threatened in this region.

Though T.K. Halli, located on Shimsha river has low degree of flow alteration, 74.98% of its length has DOF greater than 80%. This is beacause all the dams are located on the tributaries and there is no dam on the main stem of the river. Fragmentation effect of dams is getting reduced as tributaries merge with Shimsha river. Also this sub-basin hasa large network of man-made lakes which may be helpful in recharging the groundwater. Agricultural land is the dominant land cover but in this basin less water intensive crops like millets are known to be grown by farmers, reducing the pressure on groundwater reserve.

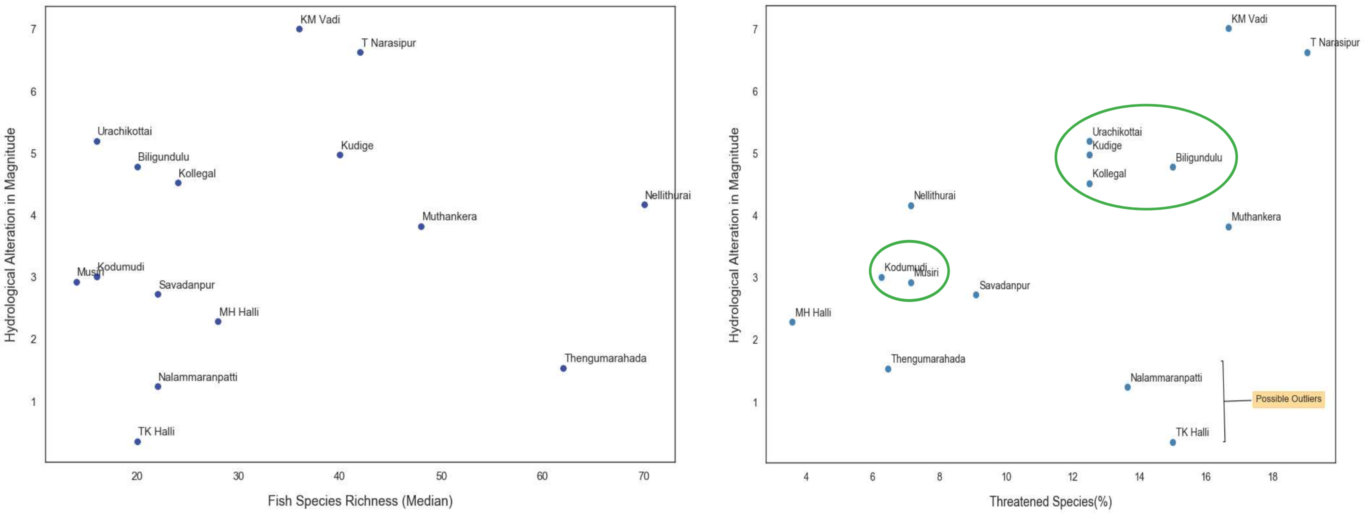
A similar situation is observed in Nalammarapati sub-basin through which Amravathy river flows. It has many dams on the tributaries of the river but none on the main stem. That's why at the location of gauge station the DOF and DOR is low. Moreover, many small dams are not included in the analysis of river fragmentation and flow regulation.

Bhavani River river is a highly fragmented river flowing through gauge stations Nellithurai and Savandapur. This basin was declared as closed due to over-allocation and also inter-basin transfer to neighbouring basins. At the confluence of Moyar and Bhavani river, Bhavani sagar dam is located. The population range of Tor Remadevi , a critically endagered fish species, is restricted to the location of dam. Environmental flows should be provided in this basin in order to save the shrinking population of this iconic fish species, endemic to Kaveri basin. Less proportion of natural vegetation is left in the basin.

5.8 Flow-Ecology Relationships

Flow alteration and ecological response relationships can correlate ecological condition of an riverine ecosystem to flow conditions. Though, other environmental stressors like water quality, sediment regulation, water temperature, river fragmentation can also affect ecological condition of riverine ecosystems, streamflow is considered as a limiting factor. An attempt to derive flow alteration ecological response relationships using available datasets was made. Hydrological alteration and fish species richness data for all the 14 sub-basins were utilised to study these relationships. Initially, relationship between hydrological alteration in magnitude and fish species richness was studied but no clear pattern was observed as seen in Fig 5.20. Then, median value for percentage of threatened species or species of concern in a sub-basin was plotted against hydrological alteration.

Fig. 5.20 Species Richness vs Hydrological Alteration in Magnitude (left) Threatened Species Richness vs Hydrological Alteration (right)



A linear increase in percentage of threatened fish species with increase in hydrological alteration in magnitude was observed with two plausible outliers. Gauge stations located on the upstream portion of main stem of Kaveri river, Kudige, Urachikottai, Biligundulu and Kollegal formed a cluster higher up on the plot with hydrological alteration in the range of 4.33 to 5.68 and percentage of threatened species in the range of (12.5 to 15%). Kodumundi and Musiri gauge stations on the downstream portion of Kaveri river, were located lower on the plot with hydrological alteration (2.79-3.11) and threatened species percentage in the range of (6.25 -7.14%). This suggests that as we move from upstream to downstream of a river hydrological alteration in magnitude is getting decreased, possibly due to inflow from other tributaries in the river network and a decline in percentage of threatened species is also observed. But the sample size is very small to draw such strong conclusion for ecological response to flow alteration. Nalammaranpati and TK Halli are two outliers where high percentage of threatened species were observed at low hydrological alteration. There can be two plausible explanation for this. They are the only two sub-basins where dams are located on the sub-tributaries and not on the main stem of the river and also a water diversion structure is located on the downstream of both the stations (Fig 5.21). Since, hydrological alteration was computed at location of gauge station, while median species richness of for the whole sub-basins was considered for the analysis, it may happen that hydrological alteration at the location is low, while percentage of threatened species is higher in the sub-basins due to other stressors.

It is necessary to study the pattern of hydrological alteration in the whole river network instead of one point location to get more accurate results. This was a limitation of this study.

Fig. 5.21 Water Diversion structure located downstream of gauge stations TK Halli (left) Nalammarapati (right)

(Source: ESRI Digital Globe Imagery)

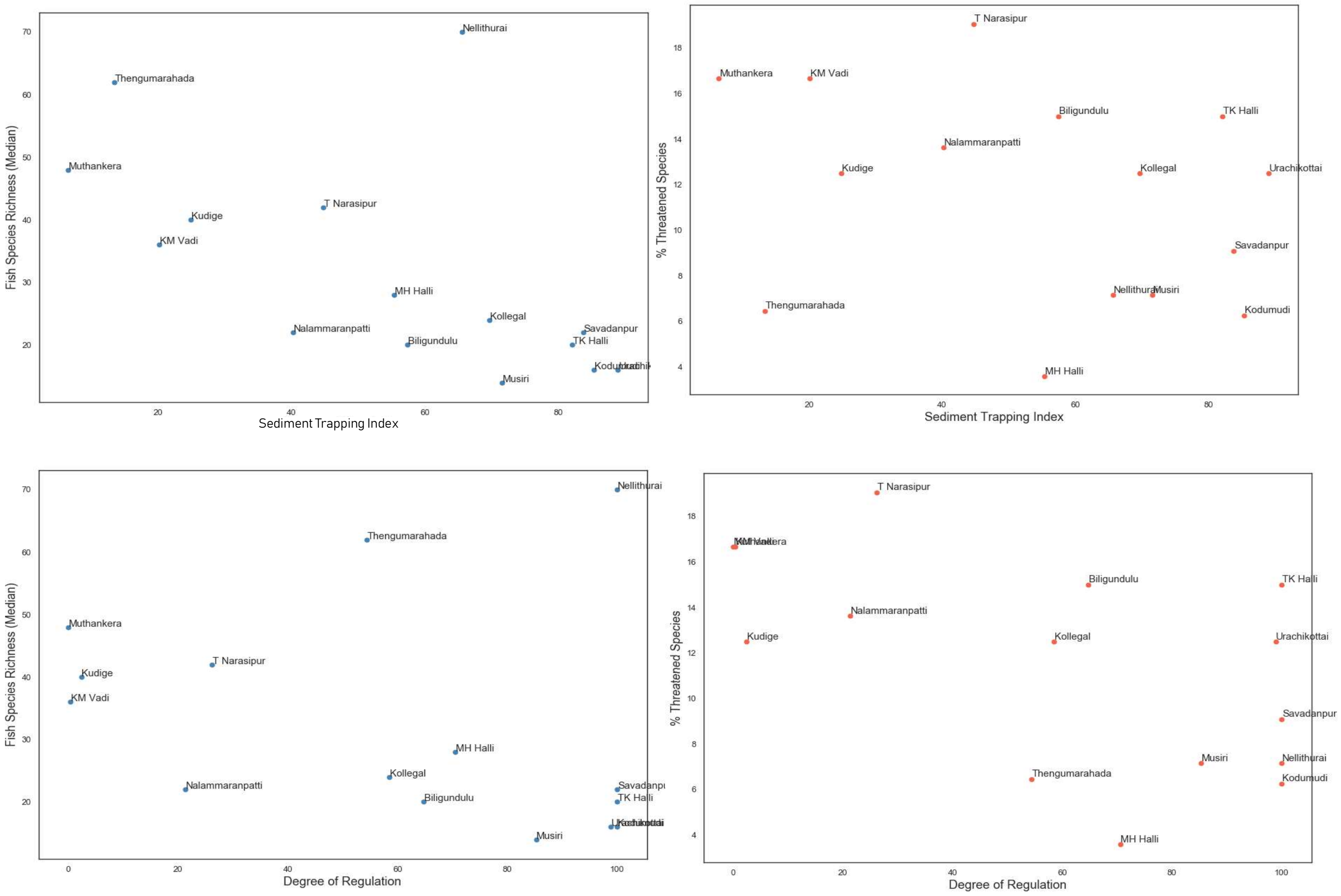
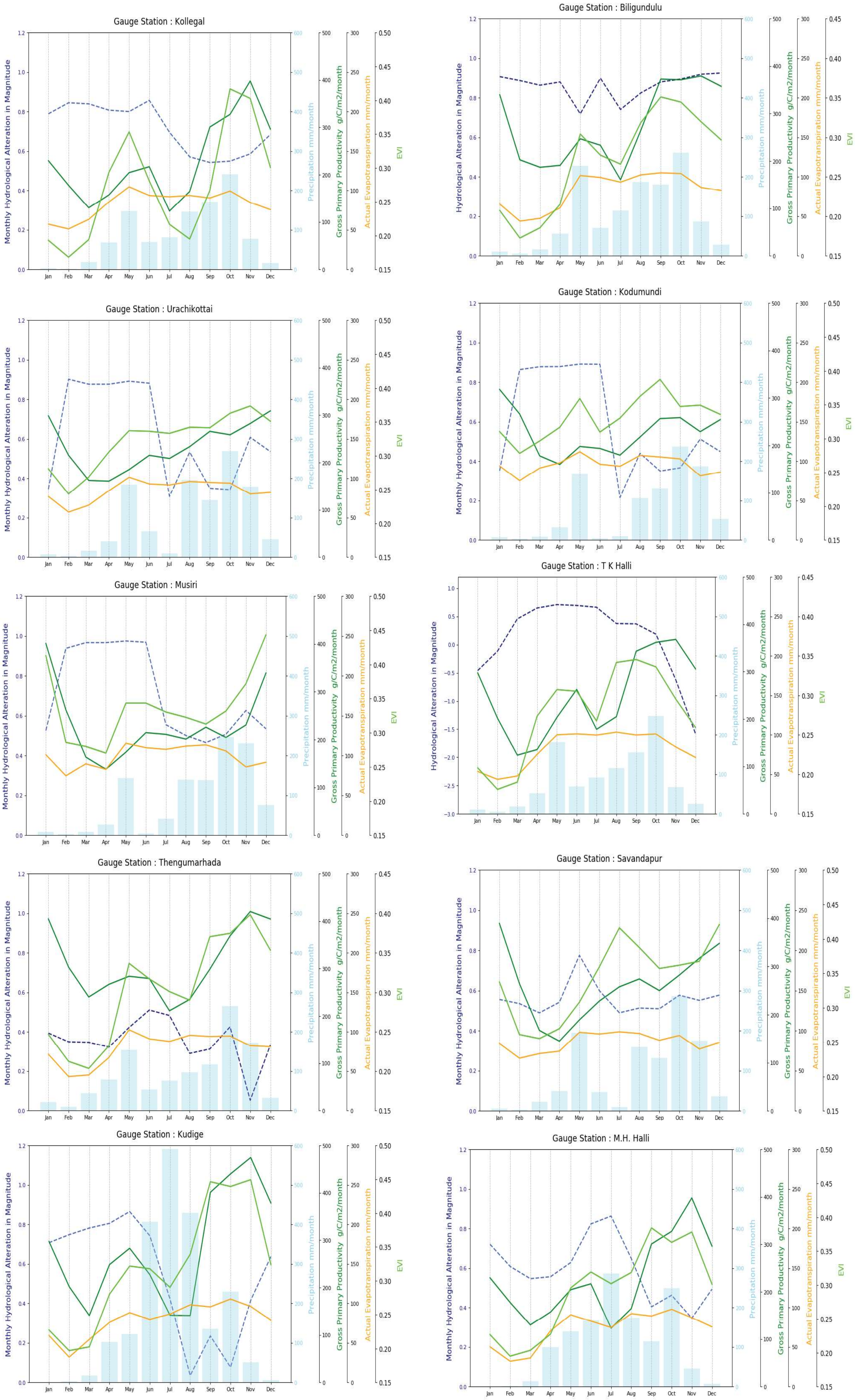


Fig. 5.22 Species Richness vs Hydrological Alteration in Magnitude (left) Threatened Species Richness vs Hydrological Alteration (right)

Similarly, an attempt to derive relationship between ecological response and other stressors like degree of regulation, degree of fragmentation and sediment trapping index was also made (Fig.5.22). Degree of fragmentation showed no definite trend to derive any conclusion. An inverse relationship between degree of regulation, sediment trapping index and median fish species richness was observed while plots with percentage of threatened species richness showed a more scattered response to the stressors. Sub-basins like Thengumarhada, Nellithurai, Kudige, KM Vadi, T. Narasipur, located at a higher elevation have high fish species richness as they form a part of Western Ghats which is a biodiversity hotspot. These basins also have high sediment trapping index possibly due to steeper slopes and large number of small dams located at higher elevation. It is difficult to draw conclusions for any concrete relationship between these stressors and natural organization of fish diversity in the basin.

Relationship between gross primary productivity (GPP) of floodplain area and hydrological alteration in magnitude was also analysed as per the procedure described in Section 4.3.2. Based on litreature review it was hypothesized that primary productivity of riparian or floodplain vegetation decreases with increase in hydrological alteration. A comparative study between gauge stations with natural vegetation and those with croplands was done. Other climatic factors like precipitation, evapotranspiration, influencing primary productivity of vegetation were also included in the study. Enhanced Vegetation Index (EVI) which is highly correlated with gross primary productivity, was also analyzed to explore the possibility of monitoring floodplain vegetation health using EVI. GPP and EVI showed strong correlation and seasonal variation with climatic factors like rainfall and evapotranspiration. An inverse relationship between GPP and monthly hydrological alteration was observed in natural as well as sub-basins with croplands, in the summer months and also during monsoon season. It is difficult to isolate the influence of flow alteration on primary productivity of floodplain as both the variables are highly correlated with climatic factors like rainfall and evapotranspiration as shown in Fig.5.23. A higher resolution spatial data for gross primary productivity or EVI might be useful in assessing vegetation response to release of environmental flows. Encroachment of agriculture lands into riparian and floodplain zone and overextraction of groundwater, limits the possibility of drawing strong relationships for impact of flow alteration on productivity of floodplain area.

Fig. 5.23 Seasonal Variation in GPP, EVI, Precipitation, Actual Evapotranspiration and % Deviation of Flow from Natural Flow Regime



Gauge Station : Kollegal

Gauge Station : Biligundulu

Gauge Station : Urachikottai

Gauge Station : Kodumundi

Gauge Station : Musiri

Gauge Station : T K Halli

Gauge Station : Thengumarhada

Gauge Station : Savandapur

Gauge Station : Kudige

Gauge Station : M.H. Halli

5.9 Discussion of overall validity of results

5.9.1 Uncertainity in Datasets

Uncertainity in evaluation of indicators for ecosystem integrity and for estimation of hydrological alteration in magnitude can be due to measurement or systematic error or due to natural variability, missing or incomplete datasets. Ground observations of river discharge is mostly recorded manually in India and missing data is extrapolated from observed points. PCR-GLOWB data was used as natural flow data in absence of natural flow records which are also not validated for most of the basins based on ground observations.

Static spatial datasets of IUCN were used to get an estimate about species richness in the basin. IUCN spatial data is compiled from regional assessments and population range map for each species is defined. Last assessment in the basin was done in the year 2010 and therefore it is not a true representative of current conditions of species diversity in the basin. Many species may have become extinct before such assessments were conducted. There is also uncertainity associated with population range maps as point observations were aggregated to get the spatial range.

Free flowing river dataset used for getting an estimate about degree of regulation, degree of fragmentation, sediment trapping index, urban area and road density index are compiled based on different global datasets which can add to uncertainity in the final results. Moreover, benchmarking of free flowing river dataset was done based on data for100 rivers worldwide. In India data for Ganges river basin was considered for the benchmarking. Hence, in order to improve the results basin scale validation is required. Some of the small dams were not included in the analysis of DOR, DOF and SED due to which index value was underestimated in some parts of the basin. This dataset is also static based on annual average discharge from WaterGap global model, so it gives a preliminary assessment of pressure factors on freshwater habitat due to dams, infrastructure development in floodplain area

Datasets used for estimation of flow-ecology relationship, Gross primary productivity, EVI, Actual Evapotranspiration, Rainfall are global datasets which are not validated based on ground observations, hence can add to the uncertainity in interpretation of results. Gross primary productivity is based on MODIS land cover map which has a coarse spatial resolution. So it is difficult to assess the primary productivity of riparian and floodplain regions where encroachment of agricultural lands restricts natural vegetation to very small areas which are not captured in the land cover maps with coarse resolution. Global floodplain dataset is based on elevation data has a coarse spatial resolution. It was not able to delineate floodplains accurately in small catchments specially in high elevation region.

5.9.2 Limitations of this study

Hydrological alterations were calculated at the location of gauge stations only. This limits our understanding of how alteration in any flow component is transmiited along the river network. Hence, an approach similar to free flowing river dataset can be adopted to understand the propogation of flow alteration in a river network. Flow alteration in only magnitude was studied in this approach. Other flow componets like frequency, duration, rate of change etc. needs to be studied as well. Free flowing river datatset was not validated for the study area. Water quality in rivers, water temperature, pesticide polltuion from agricultural fields, overfishing also impacts freshwater biodiversity but were not taken into account in this study. Sand mining is a serious threat to freshwater habitats. This was no taken into account in sediment trapping index as it is difficult to quantify.

6 SYNTHESIS

6.1 Conclusion

Using open-access global datasets for quantification of ecosystem integrity of river basins helps in getting a preliminary understanding of ecological condition of rivers and the drivers negatively affecting the ecological balance. Regional environmental flow assessments are time consuming and require a lot of resources and expertise. The rate at which freshwater biodiversity is declining, it is required to prioritize conservation actions and timely allocate water for the environment. This methodology will also assist in identifying the pressure areas for prioritising conservation and monitoring efforts and it can b easily incorporated by countries, with little know-how and resources, in conducting regional level assessments. Also, dominant pressure factor, affecting the ecological health any river can be identified using this holistic preliminary method for estimating ecosystem integrity at sub-basin scales. Periodically updated global datasets will depict current conditions more realistically and will also help in identifying environmental management objectives.

Groundwater extraction poses a serious threat to sustenance of environmental flows in basins dominated by agricultural land like Kaveri basin. It was observed that many small tributaries lost connection to the main river after the construction of dam which facilitated agriculture expansion in the region. Farmers also grew crops and vegetables on river bed during prolonged low flow periods affecting the groundwater reserve. A detailed study on impact of over-use of groundwater on the natural flow regime is required.

Flow alteration-ecological response relationships can be instrumental in identifying thresholds or setting environmental flow limits. IUCN data related to freshwater biodiversity can be utilised to develop such relationships specially in data scarcr region or where no e-flow assessments have been conducted-so far. These relationships can then be refined by collecting site specific data. Also, grouping rivers with similar characteristics can save time and resources. Insights from data rich river basins can be transferred to data scarce one. Monitoring the health of riparian or floodplain natural vegetation is also important. Currently, available datasets are of coarse resolution and have strong correlations with climatic variables like rainfall and evapotranspiration. Hence, high resolution data is needed for this purpose.

ELOHA framework, currently in use for regional e-flow assessments can be adapted for global scale holistic preliminary assessments of environmental flows. Global datasets can be used in this framework to derive flow-ecology relationships. ELOHA provides a simplistic and scientific approach to assess environmental flows in a river basin. It can help in establishing a link between regional and global prelimnary e-flow assessments. This will facilitate speedy exchange of information from global to regional level or vice-versa, thus reducing ambiguity in reporting of data. Global environmental methods should be easy to apprehend and should provide insights and guidance for carrying out higher level of assessments in a river basin.

6.2 Recommendations

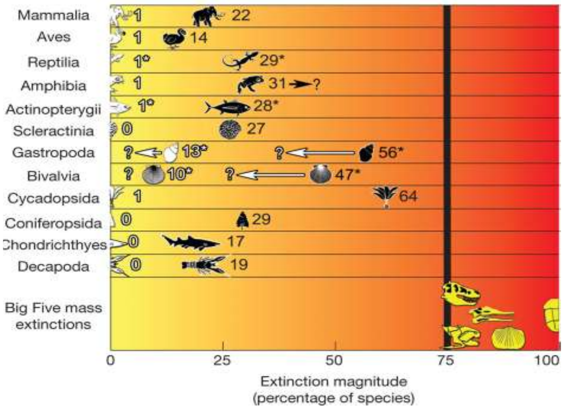


Fig 6.1 Extinction Magnitude of IUCN assessed taxa in comparison to 75% extinction benchmark. Species extinct over past 500 years (white icon); Currently threatened species with those already extinct (black icon); * very few species assessed; Arrows- Extinction % probably infalted; Big Five species losses (yellow icon) Source : (Barnosky et al., 2011)

We are amidst a sixth mass extinction of species, termed as Holocene or Anthropocene, triggered by human activities- fragmenting habitats, killing species and changing global climate. Extinctions of species are occuring faster than they would naturally occur. If all species currently threatened according to IUCN red list become extinct in next century and trend continues as usual, level of mass extinction will be reached in as soon as 240 to 540 years (Barnosky et al., 2011). If so happens recovery from mass extinction may take millions of years. It is therefore necessary to work collaboratively for mitigating stressors that are affecting freshwater habitats.

A holistic preliminary assessment framework for environmental flow is needed specially for developing countries where climatic and anthropogenic stressors are high and there is a lack of scientific assessments (Opperman et al., 2018). ELOHA framework which is used for regional assessments can be upscaled, using open source global datasets, to carry out global scale assessments. It can provide valuable insights about flow alteration-ecological response relationships. Insights from a data rich river basin to data scarce one can be transferred based on global river classification map.

Sensitive species, like fishes from Tor and Hypselobarbus genus in Kaveri basin, currently endangered due to various stressors, should be identified in every river basins and data from various sources should be hosted on a common global platform (W et al., 1AD) (Navarro et al., 2017). Process models should be developed to model affect of flow regime change on the life stages of these species (Tonkin et al., 2019). Uncertainity in future climate should also be taken into account. Synergy between global platforms IUCN, GEOBON, Allliance for Freshwater Life and Environmental Flow community is needed to accomplish the mammoth task of monitoring and assessing freshwater habitats status at a regular interval. Scientists can be encouraged or given incentives to share their field data on a common platform for speeding up future research in environmental flow science.

Preliminary assessment of Ecoystem Services should also be included in the framework for getting a better understanding of trade-offs between ecosystem service and ecological condition of rivers. (Grizzetti et al., 2019) It will also help in setting realistic targets for implementation of environmental flow.

Periodically updated global datasets should be used for estimation of ecosystem integrity of river basins. Such assessments should be repeated every 3-5 years to capture the changes in river basins and taking timely action for preserving the health of river.

Global Inland water quality product is needed to account for river pollution due to pesticides and municipal and industrial sewage discharge. Data from world water quality portal can be utilised in future (http://www.worldwaterquality.org/).

Overextraction of groundwater decreases natural discharge in rivers, affecting aquatic ecosystem severely (de Graaf, Gleeson, (Rens) van Beek, Sutanudjaja, & Bierkens, 2019). Environmental flow limits to groundwater use in a river basin should also be studied further.

ECOSTRESS dataset mapping actual evapotranspiration at a spatial resolution of 70m can be utilised to monitor vegetation in the floodplain and riparian areas. Currently this data is only available for key biomes around the world.

Appendix 1

Table 12 - Hydrologic River Classes in Kaveri Basin as per GloRic framework

S.N.	Hydrologic Class	Avergage Discharge	Flow Regime Variability	Gauge Stations
1	12	Low Discharge	Low Variability	TK Halli
2	13	Medium Discharge	Low Variability	Thimanahalli, Kanakpura, Nellithurai
3	22	Low Discharge	Medium Variability	Thengumarahada, E Managlam
4	23	Medium Discharge	Medium Variability	Sakleshpur, MH Halli, Akkihebbal, Kudige, KM Vadi, Muthankera, Savandapur, Nalammaranpati
5	33	Medium Discharge	High Variability	T.Narasipur, Kollegal, Biligundulu

Table 13 - Physio-Climatic River Classes in Kaveri Basin as per GloRic framework

S.N.	Physio-Climatic Class	CMI Index	Elevation	Gauge Stations
1	411	Low CMI	Low Elevation	Kanakpura, TK Halli, Narasipur, Kollegal, Biligundulu, Thengumarahada, Savandapur, Urachikottai, Nellithurai, Kodumundi, E Mangalam, Musiri, Nalammaranpatti
2	412	Low CMI	High Elevation	Thimanahalli, MH Halli, Akkihebbal, KM Vadi
3	422	Medium CMI	High Elevation	Kudige
4	431	High CMI	Low Elevation	Muthankera
5	432	High CMI	High Elevation	Sakleshpur

Table 14 - Geomorphic River Classes in Kaveri Basin as per GloRic framework

S.N.	Geoorphic Class	Lake-wetland influenced	Stream Power	Gauge Stations
1	11	No	Low stream power	Thimanahalli, Kanakpura, TK Halli, KM Vadi, Narasipur, Thengumarahada, Savandapur, E Mangalam, Nalammaranpatti
2	12	No	High stream power	Sakleshpur, Kudige, Kollegal, Biligundulu, Muthankera, Urachikottai, Nellithurai, Kodumundi, Musiri
3	22	Yes	High stream power	MH Halli, Akkihebbal

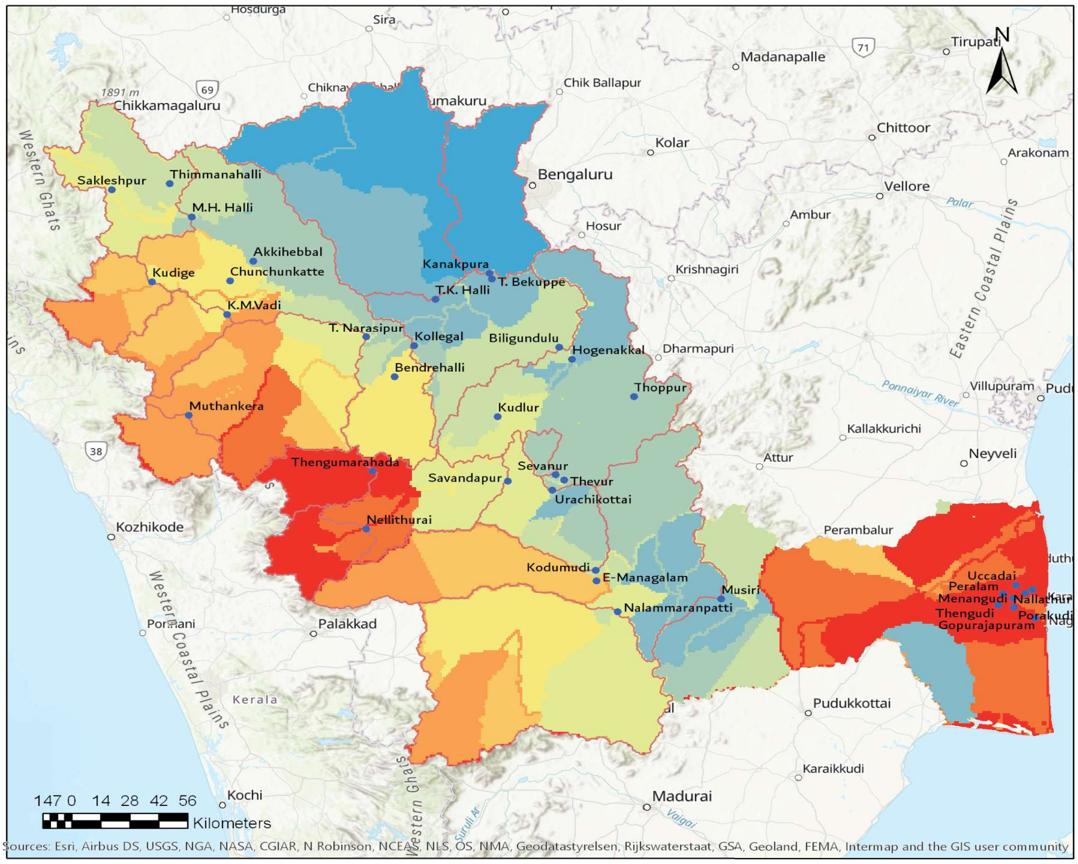
Appendix 2

Table 15 - Land Cover Naturalness : Naturalness weights assigned to Land Use/Land Cover Types

S.N.	Land Use/Land Cover Type	Weightage
1	Rainfed Cropland	30
2	Cropland - Irrigated, Post Flooding	30
3	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	60
4	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	70
5	Tree cover, broadleaved, evergreen, closed to open (>15%)	100
6	Tree cover, broadleaved, deciduous, closed to open (>15%)	100
7	Tree cover, needleleaved, evergreen, closed to open (>15%)	100
8	Tree cover, needleleaved, deciduous, closed to open (>15%)	100
9	Tree cover, mixed leaf type (broadleaved and needleleaved)	100
10	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	100
11	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	100
12	Shrubland	100
13	Shrubland	100
14	Lichens and mosses	100
15	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	100
16	Tree cover, flooded, fresh or brakish water	100
17	Tree cover, flooded, saline water	100
18	Shrub or herbaceous cover, flooded, fresh/saline/brakish water	100
19	Urban areas	0
20	Bare areas	50
21	Water bodies	200

S.N.	Classes	"Naturalness" Weightage
1	Urban Area	0
2	Agricultural Land	30
3	Bare Area	50
4	Cultural Vegetation	60
5	Semi-Natural Vegetation	70
6	Natural Vegetation	100
7	Water Bodies	200

Appendix 3



Freshwater Species Richness

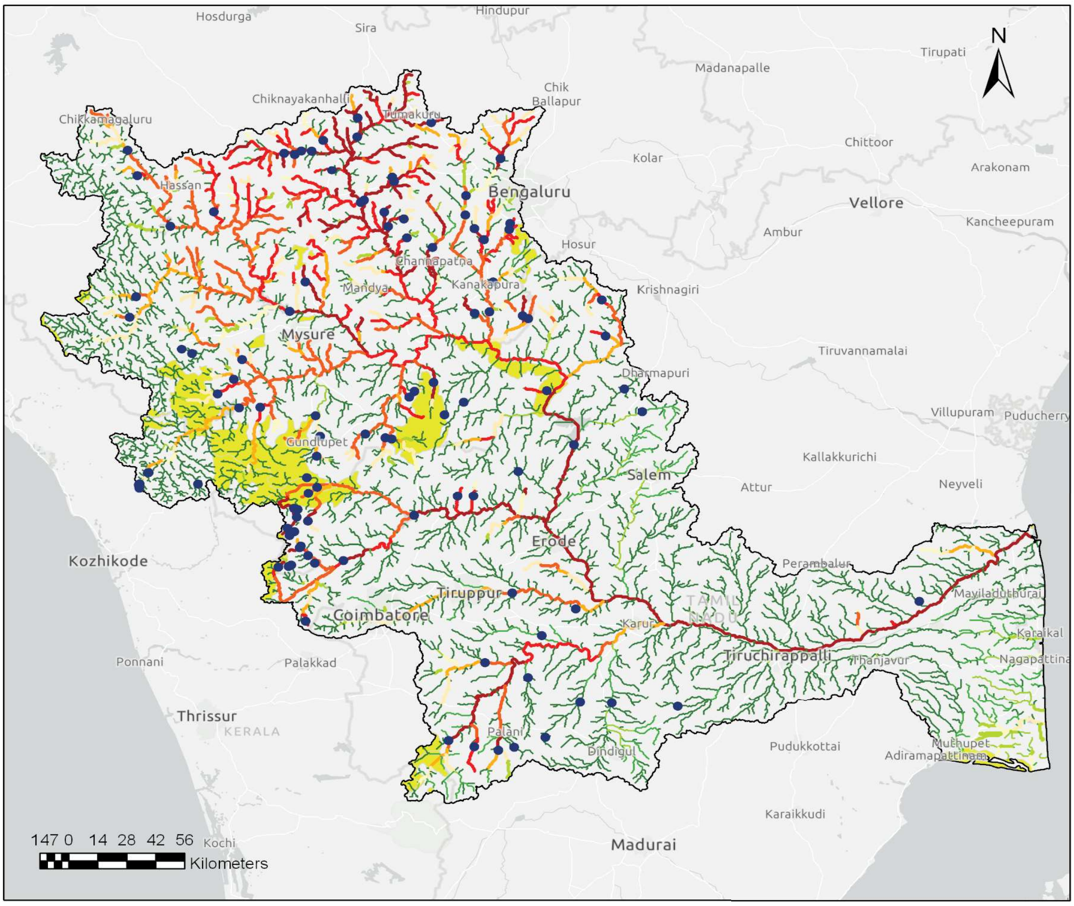
Fig. A3.1 Mapping of Freshwater Species Richness (Taxonomic Groups : Fish, Molluscs, Odonata, Crabs, Shrimps, Plants) in Kaveri basin. Data - IUCN Spatial Data

Legend
- ● Gauge Stations
- ☐ Sub-Basins Boundary

Species Richness

Value
- ≤ 304
- ≤ 312
- ≤ 325
- ≤ 335
- ≤ 351
- ≤ 378
- ≤ 392
- ≤ 431
- ≤ 442
- ≤600

Fig. A3.2 Extent of Protected Areas alongwith mapping of Connectivity Status Index in Kaveri basin. Data - World Database of Protected Areas & Free Flowing River Dataset



Extent of Protected Areas in Kaveri Basin

Legend
- ☐ Cauvery Basin
- Protected Areas

Connectivity Status Index

CSI
- ≤35
- 35 - 50
- 50 - 65
- 65 - 80
- 80 - 90
- 90 - 93
- 93 - 95
- 95 - 97
- 97 - 99
- 99 - 100

Dams
- ● Dams

Fig. A3.3 Mapping of Odonata Species Richness in Kaveri basin. Data - IUCN Spatial Data

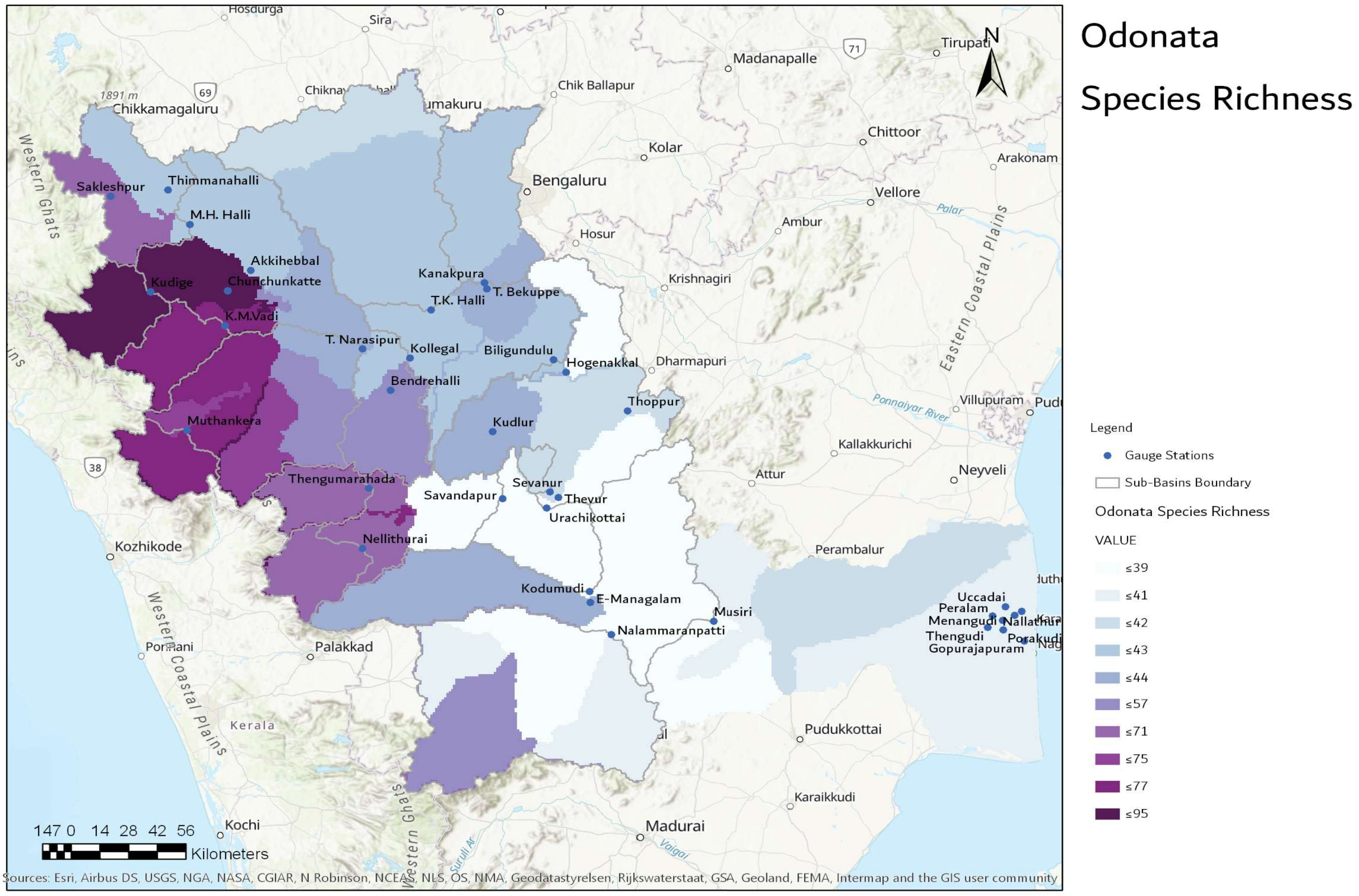


Fig. A3.4 Mapping of Molluscs Species Richness in Kaveri basin. Data - IUCN Spatial Data

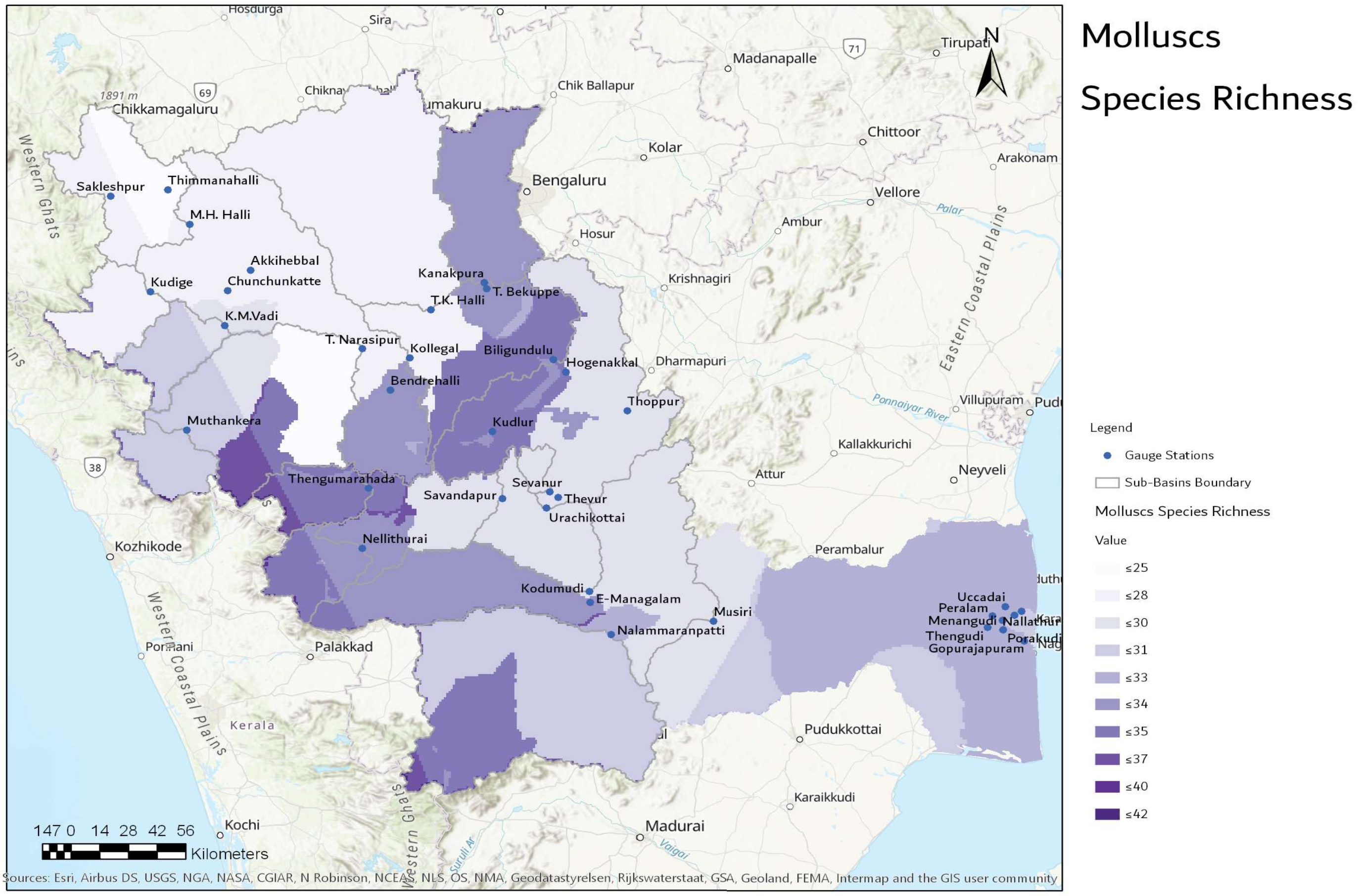


Fig. A3.5 Mapping of Shrimp Species Richness in Kaveri basin. Data - IUCN Spatial Data

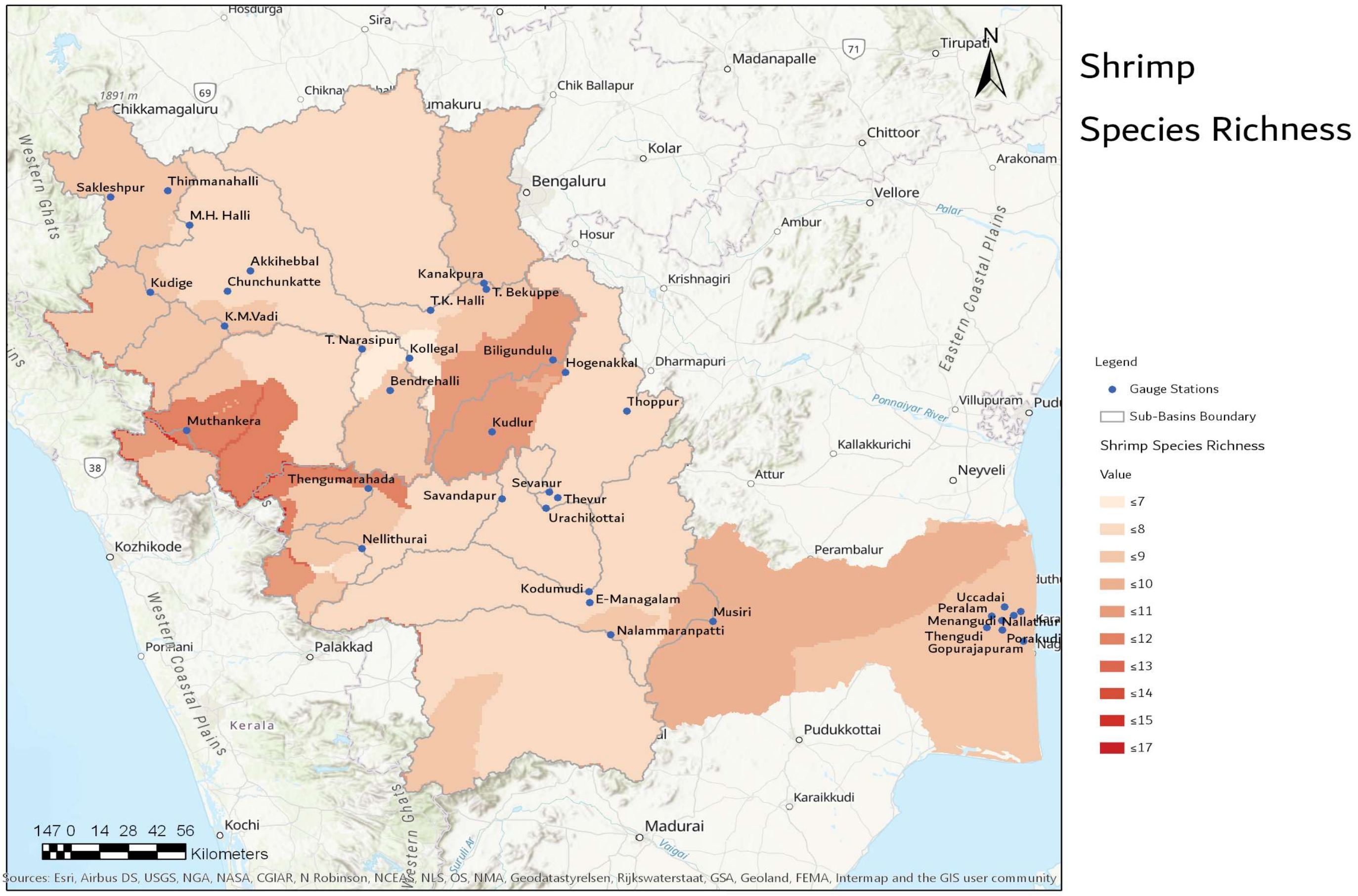


Fig. A3.6 Mapping of Crab Species Richness in Kaveri basin. Data - IUCN Spatial Data

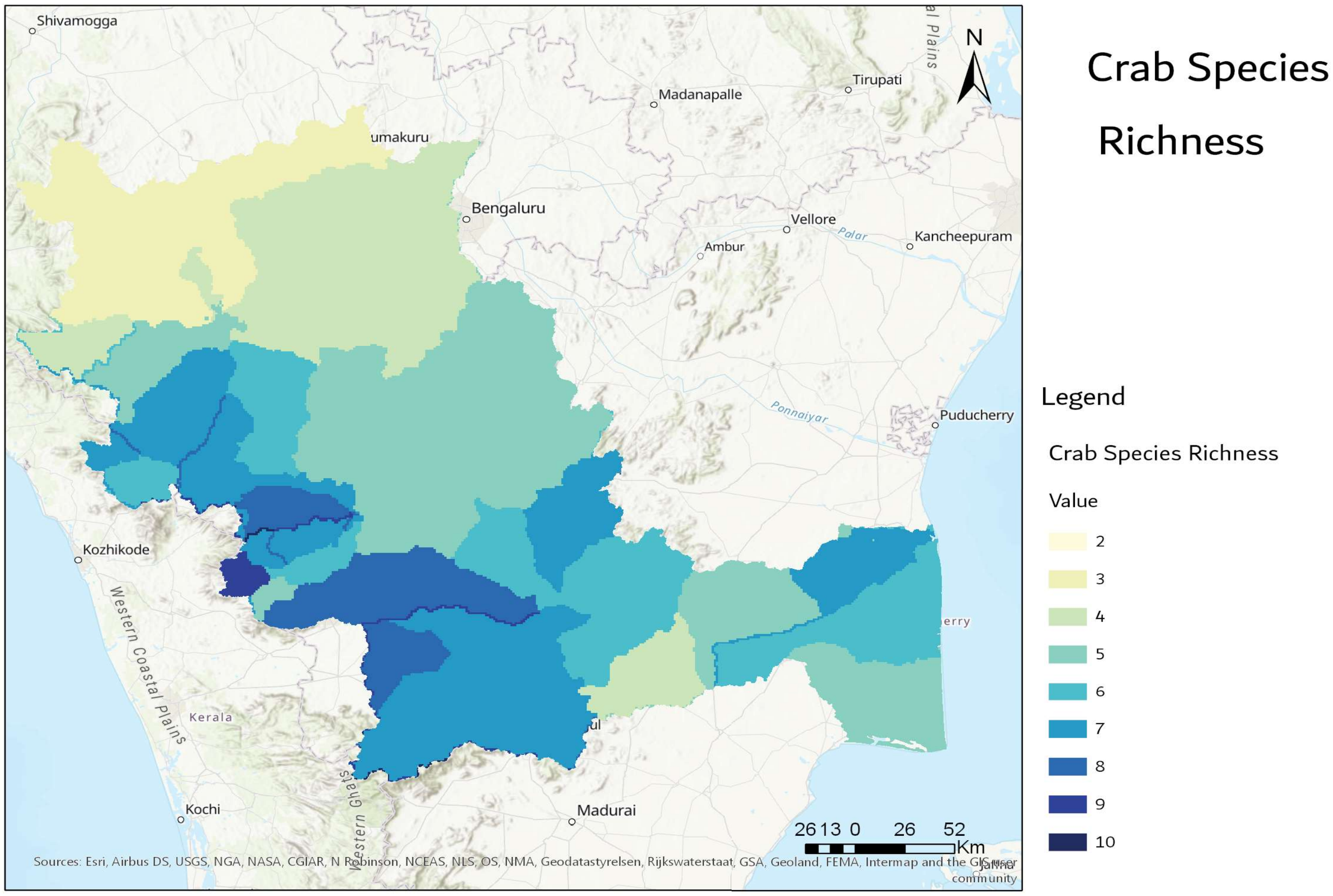


Fig. A3.7 Mapping of Plants Species Richness in Kaveri basin. Data - IUCN Spatial Data

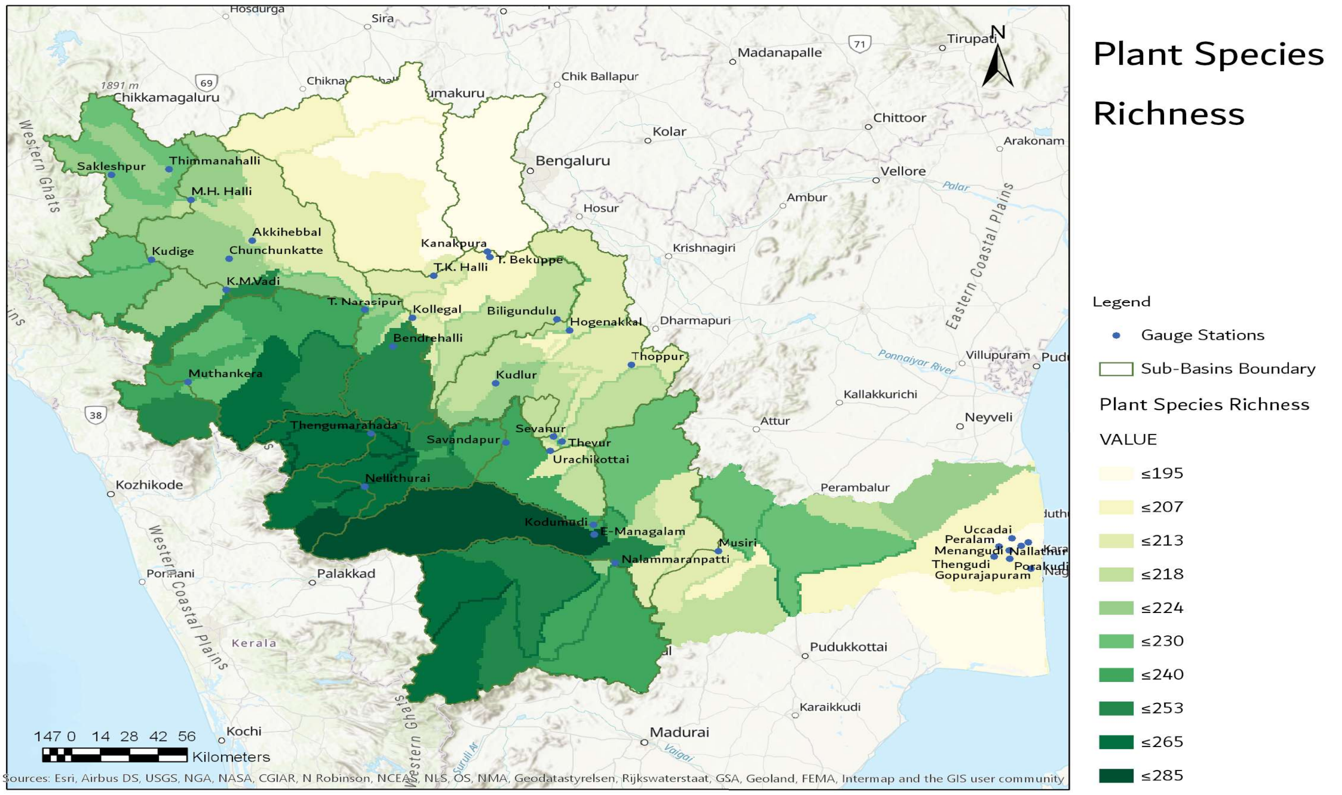


Fig. A3.8 Mapping of Plants Species of Concern Richness in Kaveri basin. Data - IUCN Spatial Data

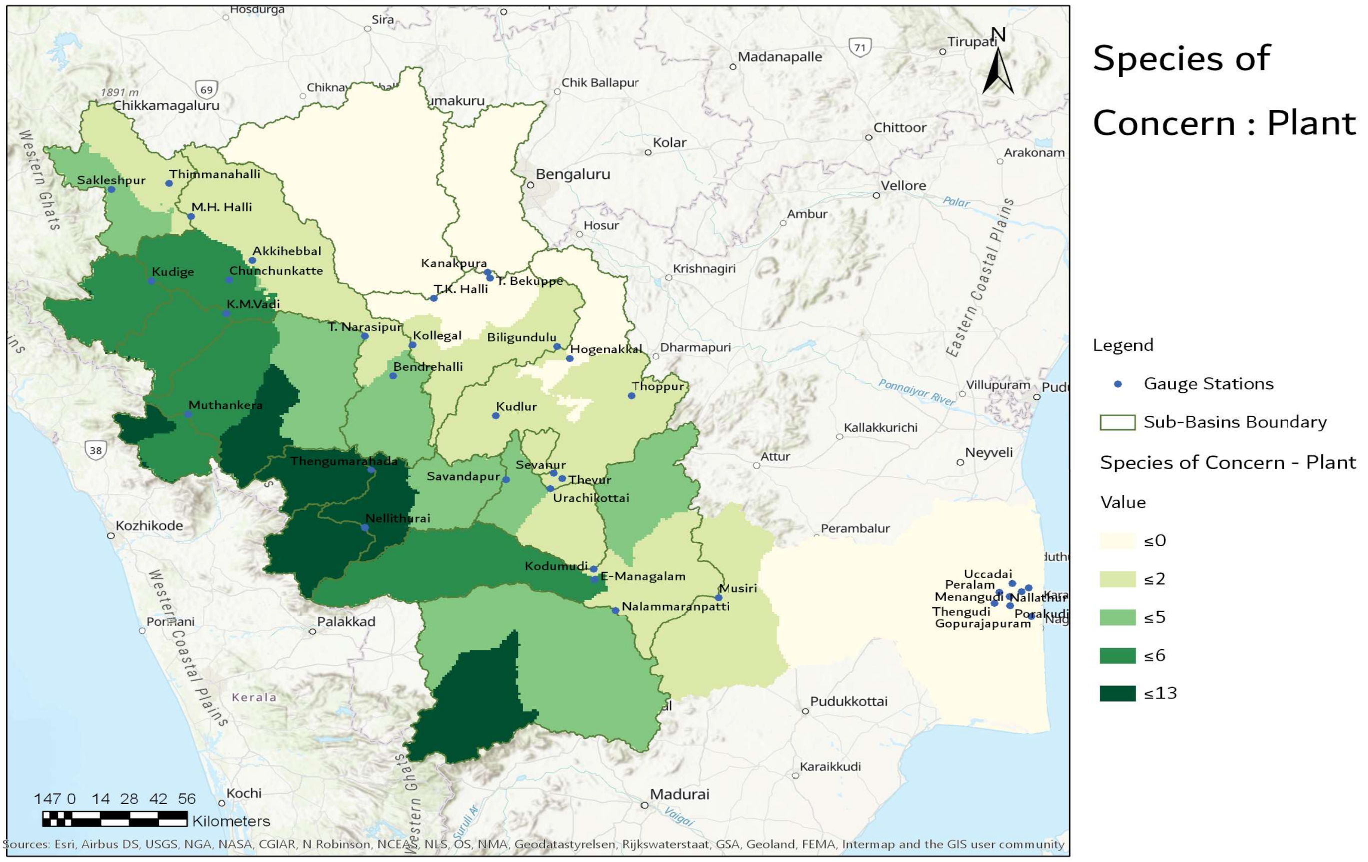
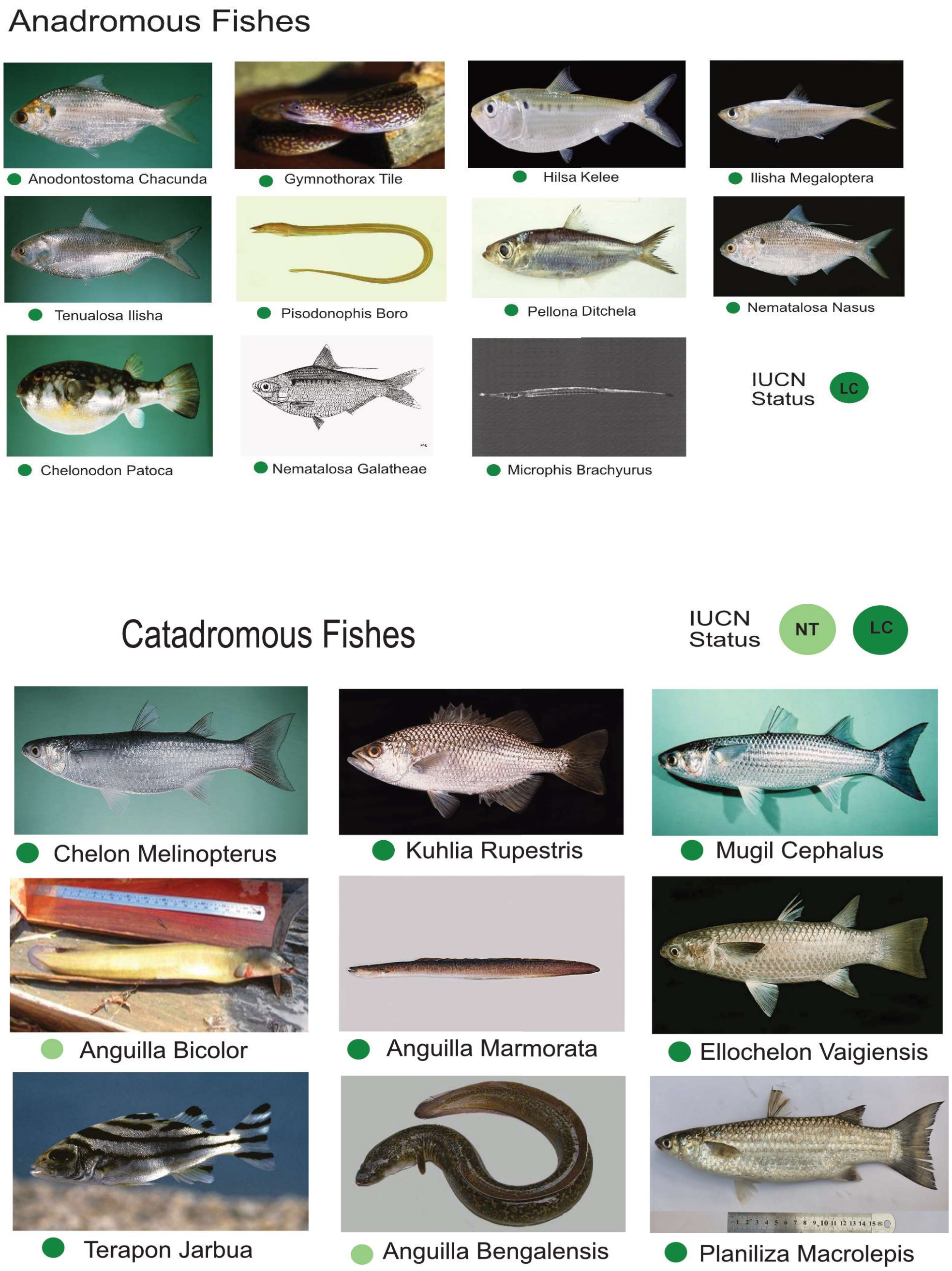
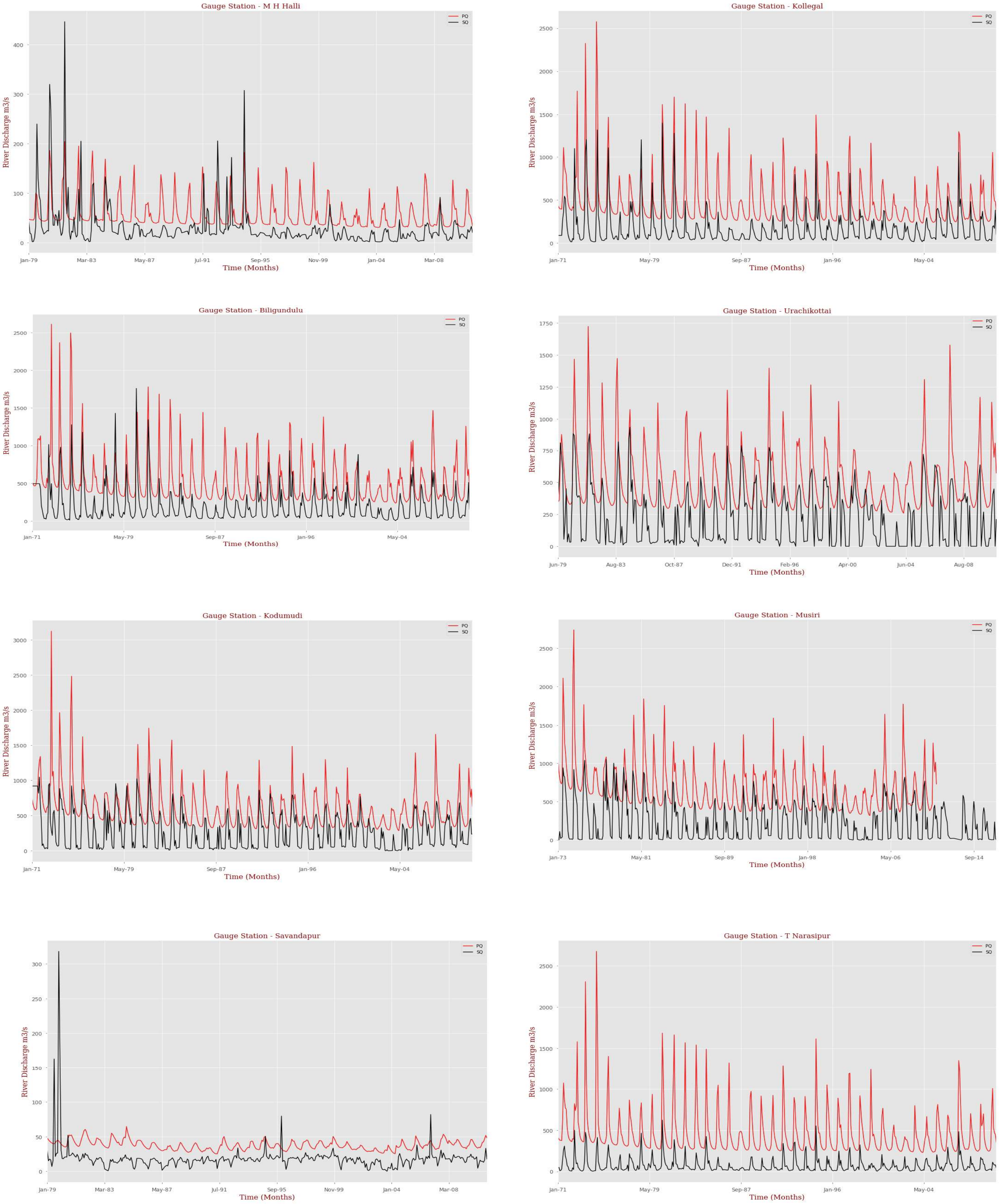


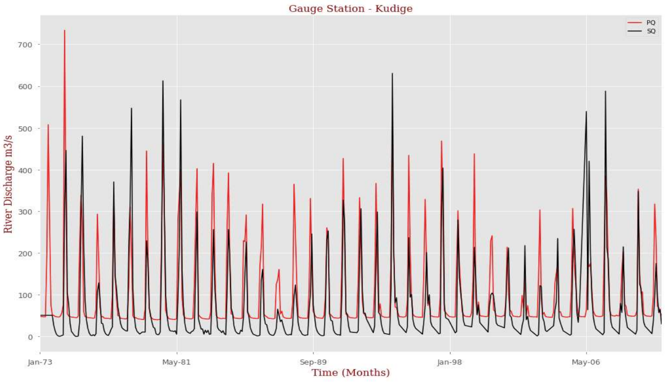
Fig. A3.9 Migratory Fishes in Kaveri Basin alongwith IUCN red list category. Anadromous (top) Catadromous (bottom)
Data - Fish Base

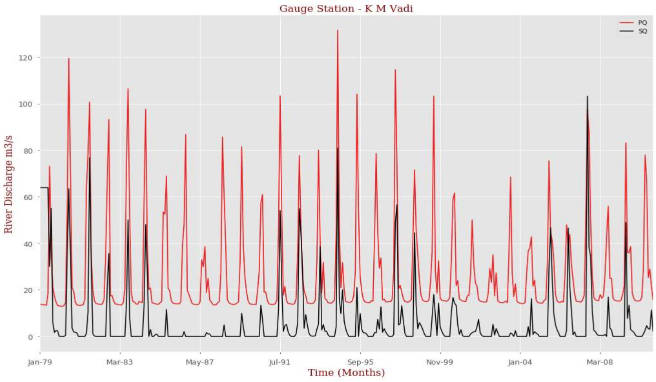


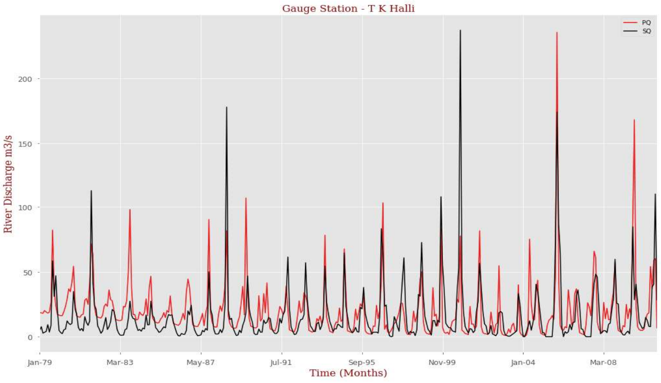
Appendix 4

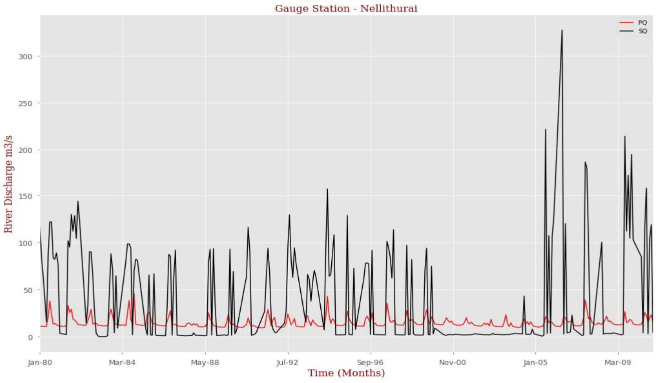
Fig. A4.1 Time series of reference natural flow (red lines) and observed flow (black lines) at 14 gauge stations in Kaveri river basin, Data - PCR-GLOWB v1 & CWC India

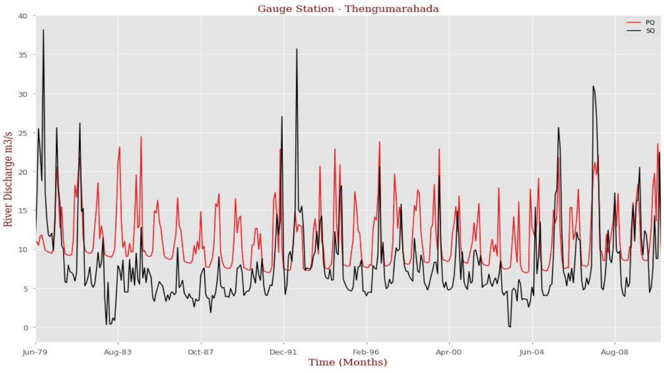



Gauge Station - Kudige
PQ
SQ
River Discharge m3/s
0
100
200
300
400
500
600
700
Jan-73
May-81
Sep-89
Jan-98
May-06
Time (Months)


Gauge Station - K M Vadi
PQ
SQ
River Discharge m3/s
0
20
40
60
80
100
120
Jan-79
Mar-83
May-87
Jul-91
Sep-95
Nov-99
Jan-04
Mar-08
Time (Months)


Gauge Station - T K Halli
PQ
SQ
River Discharge m3/s
0
50
100
150
200
Jan-79
Mar-83
May-87
Jul-91
Sep-95
Nov-99
Jan-04
Mar-08
Time (Months)


Gauge Station - Nellithurai
PQ
SQ
River Discharge m3/s
0
50
100
150
200
250
300
Jan-80
Mar-84
May-88
Jul-92
Sep-96
Nov-00
Jan-05
Mar-09
Time (Months)


Gauge Station - Thengumarahada
PQ
SQ
River Discharge m3/s
0
5
10
15
20
25
30
35
40
Jun-79
Aug-83
Oct-87
Dec-91
Feb-96
Apr-00
Jun-04
Aug-08
Time (Months)

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Odonata : Crimson Marsh Glider (Trithemis kirbyi) found on the banks of Kaveri river (Source : https://www.indianodonata.org/)

Kaveri river creating Hogenakkal Falls (known as “Niagara falls of India”) as it drops and cuts through rocky terrain in Tamil Nadu (Source :Wikipedia)

Farmers lie neck deep in Kaveri river bed with rose garlands to signify death, demanding constitution of Kaveri Water Management Board
(Source: Press Trust of India, 10 April 2018)