Drivers of fish diversity and turnover across multiple spatial scales: Implications for conservation in the Western Ghats, India

Thesis Submitted for the Degree of Doctor of Philosophy

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Declaration by the candidate

I, Vidyadhar Atkore hereby declare that the thesis entitled ***“Drivers of fish diversity and turnover across multiple spatial scales: Implications for conservation in the Western Ghats, India”*** has been compiled by me under the supervision of Dr. Jagdish Krishnaswamy, Ashoka Trust for Research in Ecology and the Environment (ATREE), Bangalore. The thesis has not been previously submitted for the award of any degree, diploma, associateship, fellowship, or its equivalent to any other University or Institution.

(Vidyadhar Atkore**)**

Place: Bangalore

Date: 30th November, 2017

Certificate

This is to certify that the thesis entitled "***Drivers of fish diversity and turnover across multiple spatial scales: Implications for conservation in the Western Ghats, India***" submitted by Mr. Vidyadhar Atkore, for the award of Doctor of Philosophy for, Manipal University, Manipal, is a record of the research work carried out by him during the period of his study in this university under my guidance and supervision and the thesis has not formed the basis for the award of any degree, diploma or other similar titles.

Dr. Jagdish Krishnaswamy

Place: Bangalore

Date: 30th November, 2017

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Dedication

I would like to dedicate this work to last remaining free-flowing tropical streams and rivers and their associated incredibly rich aquatic life

Executive Summary

Freshwater ecosystems are extraordinarily rich in their aquatic life. They sustain other terrestrial life and offer numerous ecosystem services to humankind. Fish is one of the most important components of freshwater ecosystems (Darwall et al., 2008). However, the status of freshwater habitat and associated aquatic life including that of fishes is in danger due to intense anthropogenic impacts such as small and big dams, water diversion schemes for irrigated agriculture, deforestation, removal of riparian cover, sand mining and pollution. As a result, freshwater fishes are being driven to extinction. The extinction risk for riverine fishes is believed to be far greater than terrestrial organisms, and may even have exceeded the natural rate of overall species extinction (Ricciardi and Rasmussen, 1999; Dias et al., 2017).

Studies that quantify various anthropogenic threats to biodiversity of the Tropical Asian streams and rivers are inadequate as compared to those in the temperate regions. Streams are being fragmented, disconnected and exploited heavily for rising human developmental needs. Ecologists have emphasized the need for their restoration, quantification of such threats and detail mapping of aquatic biodiversity (Strayer et al., 2010; Dudgeon et al., 2010; 2011; Araujo et al., 2013; Alexandre et al., 2013; Shimadzu et al., 2013; Sakaris, 2013; Bae et al., 2016). Therefore there is a need to address fish responses to the disturbances to the habitat at different spatial scales. Often lack of crucial information on species distribution, habitat ecology and species responses to different anthropogenic threats at multiple spatial scales impedes our ability to prioritize river conservation.

My PhD research integrates some of these ideas and quantifies the native fish diversity and factors that drive this diversity in four river sub-basins of the Western Ghat biodiversity hotspot in India. The study primarily assesses the fish diversity at multiple nested spatial scales i.e. segment, habitat, stream order, and sub-basin. Two river basins (Mhadei and Malaprabha) have numerous hydrological barriers in the form of small check dams, impoundments, barrages as well as other forms of disturbances such as substrate mining, fishing, and pollution from domestic and agricultural uses of rivers. Such disturbances have severely degraded the water quality and fish health in India (Daniels, 2002). The other two river sub-basins (Bhadra and

Tunga) are hydrologically less modified but have local disturbances such as water diversion for agriculture, plantations and pollution.

Therefore the specific research questions were: 1). How do fish species diversity (richness and abundance) vary in different river segments in four sub-basins? 2). What are the drivers of fish species turnover between river segments in a sub-basin and across adjacent river sub-basin? 3). How do fish guild richness and composition vary across regulated and non-regulated sub-basins? and 4). What is the potential for fish species recovery downstream of hydrological barriers in a river sub-basin?

To answer these research questions, I sampled fishes by using traditional fishing methods (castnet) of different mesh sizes in four river sub-basins. A stream segment was the basic sampling unit. Sampled fishes were identified in the field and released back into the water soon after taking their body measurements (total length in cm). Standard textbook and identification keys were followed (Jayaram, 2010, Daniels, 2002) and experts consulted for species level identification. Systematic and rigorous field sampling resulted in recording of 93 fish species belonging to nine orders and 18 families with 18322 individuals. Malaprabha was the species rich sub-basin (53 species) followed by Mhadei (47 species), Tunga (45 species) and Bhadra (24 species). The family Cyprinidae was dominant in all the sub-basins depicting common pattern found in South Asian rivers (Bhat, 2003; 2004). This study also resulted in the discovery of a new fish species – Kudremukh barb (*Pethia striata*) from the headwater regions of Tunga basin (Atkore et al., 2015) and reported a healthy population of critically endangered fish i.e. Wayanaad mahseer (*Barbodes wyanaadensis*) in tributaries of Bhadra and Tunga in the Kudremukh National Park. Hollow shape of the rank abundance curve suggested most species in these sub-basins are rare and few species are abundant (Magurran, 2004). At the scale of a segment- water chemistry, and at the larger spatial scales -stream order determined native fish diversity (richness and abundance) in four river sub-basins. Higher fish species richness in segments was associated with higher disturbance levels while higher abundance was associated with least disturbance. This indicates occurrence of fish recruitment (fries and fingerlings) in relatively less disturbed segments.

This study is one of the first to examine the species turnover both within and across river basins. Fish turnover was governed by stream order, stream substrate composition, canopy cover along the stream banks and water quality variables in the two basins situated within the protected area boundary. Thus, maintaining free-flowing river stretches takes on greater importance which allows persistence of diversity of stream habitats and native fish species composition. At the basin wide scale assessing the functional characteristics such as guilds of fishes and their responses to environment and various anthropogenic threats is an emerging and critical area of research in the freshwater fish community ecology (Winemiller, 2010).

Previous studies have assessed fish guild structure in a few river systems in India (Daniels, 2002; Bhat, 2003; Johnson and Arunachalam, 2010; Chakrabarty and Homechaudhuri, 2013; Kundu et al., 2014). These studies have generated important insights on fish guilds but, none of these studies have quantified either the relationship between various fish guilds and stream characteristics including water quality variables and hydrological barriers. I attempted to fill this important knowledge gap by evaluating the responses of fish guild richness to hydrological barriers and water quality variables across four river basins. The results indicated that the water column based positional fish guilds responded to diverse water chemistry variables highlighting the complexity involved in the fish-environment relationship. However, certain guilds especially surface-dwelling guilds were negatively affected due to hydrological barriers while mid-column and bottom dwelling guilds benefited from the impoundment effect (Aarts and Nienhuis, 2003; Kanno et al., 2010). This study highlights the importance of water chemistry monitoring in river basins and raises concerns over the effect of hydrological barriers on fish guild structure. This study also indicates the importance of incorporating long-term data on stream discharge and water chemistry to determine guild specific responses to either modified flow regime or changing water chemistry (Macnaughton et al., 2016).

This research also is one of the first in India and Southeast Asia to demonstrate the evidence of fish species recovery downstream of hydrological barriers in sub-basins due to the contribution of undammed tributaries and stream environmental variables. The estimated species recovery (proportion of species found in the undisturbed/control segment to that of disturbed segments) downstream of a dam was 90% at distances of 2 and 5 km. This attributed to the contribution received from the undammed tributaries. These undammed tributaries have ameliorated the water chemistry condition in the main river channel and also served as a refuge to many endemic or rare stream fishes. Based on my study catchments varying between 160 to 1332 sq.km and following the precautionary principles for conserving highly endangered biodiversity, I recommend maintaining a minimum of 5-10 undammed or undisturbed streams in a 500 sq.km sub-basin to mitigate the effect of existing or planned hydrologic barriers.

In a nutshell, this study demonstrates and highlights the importance of comprehensive field sampling effort covering multiple spatial scales within and across river basins. River basin managers could effectively use data generated from this study to formulate effective scale-dependent river conservation guidelines and monitor freshwater resources in the future.

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List of Abbreviations

AIC	Akaike Information Criteria
APHA	American Public Health Association
APHRODITE	Asian Precipitation- Highly Resolved Observational Data Integration Towards Evaluation
BD	Bottom dwelling
GLM	Generalized Linear Models
IUCN	International Union for Conservation of Nature
KNP	Kudremukh National Park
MCM	Million Cubic meters
MCD	Mid-column dwelling
MK test	Mann- Kendall’s test of significance
NRSB	Non-regulated sub-basin
NMDS	Non-metric Multi-dimensional Scaling
PCA	Principal Component Analysis
RCC	River Continuum Concept
RSB	Regulated sub-basin
SAC	Species Accumulation Curve
SD	Surface dwelling
SDC	Serial Discontinuity Concept
VIF	Variation Inflation Factor
WG	Western Ghats
WRDO	Water Resources Development Organization
ZSI	Zoological Survey of India

Chapter 1

Introduction

Freshwater ecosystems and associated habitats harbor incredible biodiversity and support human well-being. Rivers, integral part of freshwater ecosystems, offer natural flow regimes that maintain hydrological, biogeochemical and ecological connectivity between channels, floodplains, wetlands and estuaries (FIU-GLOWS, 2016). Altered or modified flow regimes disrupt the natural processes that maintain biodiversity and ecosystem function (Bunn and Arthington, 2002; Poff, 1997). River systems are under constant pressure due to increasing societal demand for both energy and water, and as a result they are heavily exploited worldwide (Winemiller et al., 2016).

Owing to such increasing threats, river systems across the globe are receiving growing conservation attention. Existing knowledge of terrestrial ecosystems are the prime driving force for aquatic ecologists to understand whether the same factors that drive species assemblage patterns in terrestrial ecosystems also drive patterns in aquatic ecosystems. Past studies conducted in temperate regions on wetland (lakes and estuaries), streams and rivers suggest that diversity patterns are largely influenced by variety of factors depending on scale (Gido and Jackson, 2010; Matthews, 1998; Winemiller et al., 2008). For instance, both biotic (competition, predation) and abiotic factors (catchment characteristics, stream channel morphology, habitat heterogeneity, water chemistry, changes in land use pattern and disturbance regime) influence species richness patterns at local, regional, basin or continental scales. In lake ecosystems, depth is a crucial factor that defines species richness patterns, while in rivers and streams, the natural flow regime is found to be the important variable maintaining habitat as well as stream biota (Bunn and Arthington, 2002; Poff, 1997; Poff and Allan, 1995).

This idea was recognized by temperate river ecologists who formulated the River Continuum Concept (RCC) (Vannote et al., 1980), which states that stream biota are shaped by energy flowing from the headstream to downstream areas. This idea has generated wide interest among river ecologists globally. Since then, numerous studies tested and replicated this both in temperate as well as tropical regions. This concept only considers river/stream as a single unit and does not take into account lateral connectivity. The Floodplain Concept emerged as a criticism to the RCC idea. Since river systems have been appropriated world-wide by dams and barrages, many scientists believed that the modified flow regime of the rivers has affected the river-dependent biota. These river barriers have fragmented riverine habitat into single or isolated habitats which gave rise to The Serial Discontinuity Concept (Ellis and Jones, 2016; Stanford and Ward, 2001; Stanford et al., 1996). All these concepts consider rivers as isolated entities and do not acknowledge the contribution from the terrestrial ecosystems in which they flow, and do not consider the fact that they are laterally connected ecosystems. This important gap was recently bridged by the idea of the Riverine Ecosystem Synthesis (Thorp et al., 2008) which consider rivers as integrated laterally connected systems. This holistic approach to studying rivers has been widely applied across the globe, especially focusing on key taxa such as macroinvertebrates and fishes since these groups are considered as biological indicators.

Studies focusing on stream/river ecosystems till date suggest that riverine biodiversity (species richness, abundance, species turnover and composition) is influenced by various factors either independently or in combination. The importance of these factors in influencing biodiversity is scale dependent. Global analyses on fish richness suggest that river size (surface area of the drainage basin and mean annual river discharge) and to a lesser extent, energy availability (net primary productivity), are important factors influencing fish species richness patterns (Oberdorff et al., 1995; 2011). At local scales, physical factors appear to determine species richness in variable environments, biological ones being more important under stable environmental conditions (Oberdorff et al., 1995; 2011). At regional and geographical scales, physical factors such as river size and climate along with historical factors such as speciation rates and dispersal are major determinants of species richness (Oberdorff et al., 1995; 2011). Patterns and processes observed in local assemblages are determined not only by local mechanisms acting within assemblages but also result from processes operating at larger spatial and temporal scales (Oberdorff et al., 1995; 2011). However, these patterns and processes are also influenced by anthropogenic impacts such as hydropower projects, river linking projects, deforestation, pollution and introduction of invasive species. Such increasing anthropogenic impacts on river systems have imperiled a significant proportion of freshwater biodiversity leading to freshwater species extinction (Chakona and Swartz, 2012; Ricciardi and Rasmussen, 1999). A recent estimate based on modelled richness and river drainage relationships under climate change scenarios suggest that fish extinction may vary from 4-22% and might accelerate further under severe water scarcity (Tedesco et al., 2013).

Tropical and sub-tropical river systems have been extensively studied in terms of their fish biodiversity in relation to various anthropogenic impacts (Bailly et al., 2016; Dudgeon, 2000; 2006; Pandit and Grumbine, 2012; Unmack, 2001; Winemiller et al., 2008). In the past, limnological studies have assessed the relationship between water quality variables and fish diversity in lakes as well as in stream environments (Chapman, 1996; Lowe-Mc-Connell, 1975; 1987; Merz, 2013; Mattos et al., 2014). Studies demonstrated that habitat heterogeneity, stream characteristics and elevation influence fish species richness within as well as across river systems (Gilliam et al., 1993; Piet, 1998; Arunachalam, 2000; Araujo et al., 2008; Mendonca, 2005; Phomikong et al., 2015). Recently, numerous studies have examined the impact of dams on fish communities and have found that dams disconnect river habitats which influences fish community structure based on functional traits (Arthington, 2004; Arthington et al., 2014; Bhat and Magurran, 2007; Chakrabarty and Homechaudhuri, 2013; Vasconcelos et al., 2014a, b). However, few studies evaluate species composition and recovery downstream of dams (Storey et al., 1991; Jeffree et al., 2001).

Past studies on fish community structure in the Western Ghats region in India

Although studies on patterns of fish diversity, distribution and conservation are on the rise, there are still large gaps in knowledge regarding fish diversity from the Western Ghats (WG) biodiversity hotspot in India. Previous studies have quantified the relationship between fish diversity and associated abiotic factors at local and regional scales (Bhat, 2002; Johnson and Arunachalam, 2009; 2010; Raghavan et al., 2008). In the southern WG, fish abundance was significantly correlated with stream habitat characteristics, mainly area and volume (Johnson and Arunachalam, 2010). Studies also identified habitat utilization patterns of fishes and found five habitat use guilds. These studies were able to reconstruct a clear pattern of fish segregation in east and west flowing rivers of this region (Johnson and Arunachalam, 2009). In another study, fish species richness increased with increasing stream order and decreased with increasing elevation (Raghavan et al., 2008). This study also found a clear temporal pattern where fish species richness was highest during the day and lowest at dusk.

In the central WG, high fish species richness was recorded in four river systems (Bhat, 2005; Bhat and Magurran, 2007). Fish in these rivers were also found to show ecological and morphological partitioning. When the impact of disturbance on fish communities was examined, it was found that natural and unimpacted rivers (Aghnashini and Bedthi) had more structured species distribution than rivers with disturbance (Sharavati and Kali). Most of these studies suffer from several shortcomings; in particular, they did not consider river-basin-wide approach and were either focused on one or few river systems. Many of these studies also lack comprehensive data on water chemistry, and thus are unable to link how fish diversity is influenced by certain crucial water chemistry variables. For most of these river systems, there is no information regarding the relationship between disturbance regimes and functional traits of fish or quantification of species recovery in rivers with dams.

To fill this important knowledge gap in our understanding of the WG fish assemblage, I studied the drivers of native fish diversity at multiple spatial scales both within as well as across four river sub-basins of the WG region, in India. A basin-wide approach is known to offer a unique opportunity to study complete fish community organization at multiple spatial scales.

Study river basins

In this study, I focused on four river sub-basins - Mhadei, Malaprabha, Tunga and Bhadra. The detailed description of each sub-basin can be found in Chapter 2 and 3.
Of the four sub-basins, Mhadei is the only west flowing sub-basin that originates within the hilly region of Bhimgad Wildlife Sanctuary at Panshet cha nala at 760 m in Belgaum district of Karnataka state. The river flows through North Goa and finally

meets the estuary at Panaji in the state of Goa (Ibrahampurkar, 2012). Malaprabha, an east flowing tributary of Krishna river also originates in Belgaum district near Kankumbi hills at 760 m elevation. It flows through Belgaum and Dharwad districts before draining into Renuka Sagara reservoir at Soundatti, situated downstream, at a distance of 300 km (Atkore et al., 2012). Both these river basins are exposed to a variety of anthropogenic disturbances such as check dams, barrages, inter-basin water transfer canals, water uptake for irrigation (sugarcane fields, oilseed and rubber-oilpalm plantation), pollution, substrate mining, illegal fishing and vehicle washing among other disturbances.

Bhadra and Tunga are the two other rivers originating in the WG region of Kudremukh National Park, at an elevation 1160 m. Both these rivers flow in opposite directions. Bhadra drains southwards into the Kudremukh range while Tunga drains northwards into Kerekatte range forming Bhadra and Tunga sub-basins respectively. There are numerous perennial streams joining each river, giving rise to a diverse range of habitats such as cascades, pools, runs and riffles. The topography in Bhadra basin is steeper than in Tunga basin and there are barely any major hydrological barriers on these rivers except a few natural waterfalls.

Objectives of the study

This study attempted to understand the drivers of native fish diversity at multiple spatial scales both within as well as across river basin. I digitized and delineated the stream network in each basin using GIS tools. The sampling in each basin was spread across different gradients viz. head stream to lower streams, different stream orders, and across habitat types to cover multi-spatial extent. A stream segment of 150 m length was determined as the basic sampling unit for the study which was nested in one, two or more habitat types within a segment. A segment was nested within a stream, a stream was nested within a sub-basin and a sub-basin was nested within an eco-region. At each segment, I collected data on stream characteristics as well as water chemistry variables. Details of study design can be found in Chapter 2, 3, 4 and 5.

In the second chapter, I examine the relationship between predictor variables such as stream characteristics and water chemistry variables with response variables such as species richness and abundance across sampled stream segments. I used Principal Component Analysis (PCA) to determine key variables that influenced the fish diversity. Then I used Generalized Linear Models (GLM) to uncover the relationship between fish richness and abundance and environmental variables including disturbance regime.

In the third chapter, I analyzed the drivers of species turnover in two adjacent river basins i.e. Bhadra (670 sq. km) and Tunga (328.60 sq. km) which were similar in their geography. I used Mantel's correlogram and Bray-Curtis dissimilarity index (species-presence absence plus abundance data) to understand the spatial autocorrelation between and across sampled segments at various distances within each sub-basin. I compared my results with similar studies carried out elsewhere from tropical river systems.

The fourth chapter evaluates the relationship between hydrological barriers (check dam, barrages), and local environmental variables with fish guild richness in similar stream orders, elevation and habitat types in four sub-basins. Two analytical techniques used were Non-metrical multi-dimensional scaling (NMDS) approach (uses species abundance data to build a Bray-Curtis dissimilarity matrix) and GLM. First, I classified all the sampled fish into various fish guilds following standard literature (Welcomme, 1985; De Silva et al., 1979; Aarts and Nienhuis, 2003; Winemiller et al., 2008; Chakrabarty and Homechaudhuri, 2013; Kundu et al, 2014). NMDS was used to investigate whether the river basins differ in their guild species composition. I then examined what factors drive guild species richness across studied basins using GLMs. Box and whiskers plots were used to determine the relationship between fish richness and abundance with water quality and environmental variables.

Finally, I evaluated species recovery patterns of stream fish assemblages in one river basin (Malaprabha) to test the hypothesis that, the species recovery will improve downstream of a dam due to the contribution of undammed tributaries joining the main river channel and that recovery improves with increasing distance from dam. To test these hypotheses, I first calculated species recovery i.e. proportion of species found downstream of dams, out of total and endemic species richness recorded in the upstream control segments unaffected by the dam. I used two types of GLM's (logistic model and asymptotic exponential model) that reflected different predictions about how species recovery was expected to increase. I also calculated the cumulative impact of dam by measuring actual distance from each of the dams using GIS. Spearman's correlation was used to find the relationship between the recovery (total and endemic species recovery) with various environmental and water quality variables.

I conclude with a synthesis of the findings from each research question investigated and further discuss the conservation implications of this study for WG rivers.

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Chapter 2

Patterns of fish diversity across river basins in the Western Ghats hotspot

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Patterns of fish diversity across river basins in the Western Ghats hotspot

Introduction

Biodiversity is influenced by different factors across different spatial scales (DeFries et al., 2010; Gaston, 2000). Ecologists, over the last few decades, have increasingly focused on understanding the factors influencing biodiversity at different spatial scales, from the local to the global. It is often thought that local-scale diversity is influenced by species interactions (Jackson et al., 2001; Matthews, 1998) while at larger spatial scales, processes of diversification and dispersal (Oberdorff et al., 2011; Olden et al., 2010) influence diversity. There have been extensive studies on terrestrial ecosystems and the scaling of biodiversity (MacArthur, 1972; Rozenweig, 1995; van Jaarsveld et al., 1998; Schwartz et al., 1999; Poiani et al., 2000). However, aquatic and river systems can also be studied using a similar framework, and such studies are providing insights into the distribution and organization of aquatic communities across spatial scales. River systems, however, have some distinct characteristics as they are embedded within distinct topographically defined catchments, and this limits species dispersal both within (due to the stream flow from upstream to downstream and river barriers e.g. waterfalls) and between river basins. Fish diversity within river systems is also governed by different factors at different spatial and temporal scales (Hugueny et al., 2010; Oberdorff et al., 2011).

Fish diversity at local scales (stream length between 100-150 m segments) is influenced by abiotic factors, water chemistry (Matthews, 1998), habitat structure (Gorman and Karr, 1978), as well as biological interactions (Holomuzki et al., 2010; Jackson et al., 2001). At the regional or eco regional level (100 - 1000 sq.km) species interactions are driven by catchment area, stream flow (Jackson et al., 2001), land-use characteristics (Schlosser, 1991), pollution (Magurran and Dawn, 2001) hydrological regulation (Sakaris, 2013) and disturbance regime (Dornelas, 2010). Fish communities are also structured across temporal scales; at much longer i.e. historical or evolutionary time scales, they are shaped by speciation rates and dispersal (Olden et al., 2010; Oberdorff et al., 2011), while at much shorter temporal scales (months to years) they are influenced by seasonality, flow variability and factors such as frequency and magnitude of flood events (Bunn and Arthington, 2002; Jardine et al., 2015). Over the last few decades, ideas from community ecology (i.e. species-area relationship, latitudinal gradient in diversity etc.) have been widely applied in tropical river systems especially in the Latin America (Araujo et al., 2008; Maltchik, 2010; Tondato, 2010), Australia (Pusey et al., 1998; Unmack, 2001), New Zealand (Astorga et al., 2014; Burridge et al., 2008) and in South East Asia (Edds, 1993; Wikramnayake, 1990; Yap, 2002) to understand patterns of diversity and its scaling. However, our understanding of diversity, distribution and habitat ecology of many threatened freshwater fish groups in India is incomplete especially across spatial scales (Bhat, 2003; Molur et al., 2011).

In regulated basins, river discharge has been identified as the main driver of fish diversity (Bunn and Arthington, 2002; Bhatt, 2012), but fish distribution is also influenced by water chemistry or the "quality of water" from the viewpoint of fish biology and ecology (Menni et al., 1996; Alabaster, 2013) which in turn influences both species as well as functional diversity (Menni et al., 1996; Brasher, 2003; Pool et al., 2010; Macnaughton et al., 2016). For instance, water temperature and conductivity regulate fish movement and abundances of certain fish species (Chapman, 1996; Abes and Agostinho, 2001) whereas stream flow modifies fish-environment relationships via water chemistry variables (Fialho et al., 2008). In addition, different fish guilds are affected by artificial or seasonal discharges from dams. For instance, rheophilic-surface dweller-sensitive fish guilds which require running water habitat (run/riffles) (Winemiller and Jepsen, 1998; Vokoun, 2009) are negatively affected due to reduction of water connectivity below dams and barrages and at the same time, eurytopic-bottom dwelling-generalist fish guilds may benefit due to impoundment effect of dams (Vokoun, 2009; Chakrabarty and Homechaudhuri, 2013; Macnaughton et al., 2016). Certain river segments, especially in hydrologically regulated river systems, are exposed to higher water temperature, changes in water quality (e.g. increase in the calcium hardness concentration, reduction in dissolved oxygen level and anthropogenic disturbance). The responses of diverse fish guilds are complex as their preferred water chemistry environments are largely unknown (Chea et al., 2016 a, b).

Studies from the Western Ghats (WG) region, a global biodiversity hotspot, have documented diversity and distribution patterns associated with biotic and abiotic factors at both local to regional scales focusing on single or few river systems but not entire basins except one study on the Godavari basin (Khedkar et al., 2014). Past research has shown a clear pattern of segregation in fish assemblages in east and west flowing rivers of the WG region (Johnson and Arunachalam, 2009). It was demonstrated that fish abundance was significantly correlated with stream habitat characteristics, mainly habitat area and volume (Johnson and Arunachalam, 2010). In the central WG, research has shown the presence of high fish species richness in four river systems with ecological and morphological partitioning of fishes in these rivers (Bhat, 2003, 2004; Bhat and Magurran, 2007). It was also found that, more natural and less impacted rivers (Aghnashini and Bedti in WG) had higher species richness than rivers with higher disturbance and hydrological modification (Sharavati and Kali in WG). In the southern WG, fish species richness increased with increase in stream orders and decreased with increasing elevation (Raghavan et al., 2008) while endemic fish richness peaked at mid-elevations (Abraham and Kelkar, 2012). While these studies provide valuable information, basin-wide surveys provide a more holistic understanding of community organization at multiple spatial scales that is essential for fish conservation as a part of river basin management (Hauer and Lamberti, 2007; Olden et al., 2010; Tedesco et al., 2012). Many small-to-large hydroelectric power projects are being developed in this global biodiversity hotspot and the absence of baseline and site specific data on fish species richness, distribution, and life history traits severely constrains conservation planning. These data will not only enable in establishing linkages between fish communities and their environmental factors, but can also form a basis for guiding river management plans in future.

Against this background, I examined patterns of diversity and distribution of freshwater fishes in four river sub-basins in the central WG, India. The specific objectives were to:

a) Examine patterns of fish species richness and abundance in four sub-basins

b) Investigate environmental drivers of species richness and abundance in these rivers, and

c) Determine the effect of disturbance on fish species richness.

I hypothesized that water quality parameters, especially dissolved oxygen, electrical conductivity, etc would influence fish species richness (Merz, 2013; Sheldon and

Fellows, 2010; Mattos et al., 2014). Fish species richness is also expected to be higher in the least disturbed segments due to the habitat complexity and available food resource (Grenouillet et al., 2002) than more disturbed segments.

Materials and Methods

Study river basins

I studied fish diversity in four sub-basins in the WG namely, Bhadra, Tunga (both non-regulated), Malaprabha and Mhadei (both regulated) situated in the states of Karnataka and Goa (Fig. 2.1). Each of these river basins is discussed in detail below:

(1) Malaprabha originates near Kankumbi village in Belgaum district of Karnataka state at 790 m elevation (Figure 2.1a). Malaprabha is an east flowing river with few seasonal streams and is the principal tributary of river Krishna. The catchment area is largely dominated by tropical wet evergreen forest in the northern side and semi-evergreen forest in the southern side of the river basin (Malkhede, 2003). Over the last decade, the cropping pattern along the river has shifted from legume (pulse crop) and cotton to sugarcane (Heller et al., 2012) resulting in large abstraction of ground and surface water, leading to reduced streamflow especially in dry-season. The river is exposed to a range of disturbances from headstream region near Kankumbi to downstream region at Khanapur. These include inter-river basin irrigation canal, abstraction of water, construction of temporary embankments/impoundments, sand-and-boulder mining and solid waste and untreated domestic sewage disposal from towns. As a result of this, the environmental and ecological health of the river has deteriorated rapidly. Therefore I classified this river sub-basin as a regulated sub-basin. (2) Mhadei is a west flowing river that originates near Degaon at an elevation of 685 m in the WG of Karnataka state. The river traverses through North Goa and finally meets the Arabian Sea in Panaji, Goa. The headwater region has numerous streams and some of the principal tributaries include Kalasa and Bhanduri. The Karnataka government has a long-

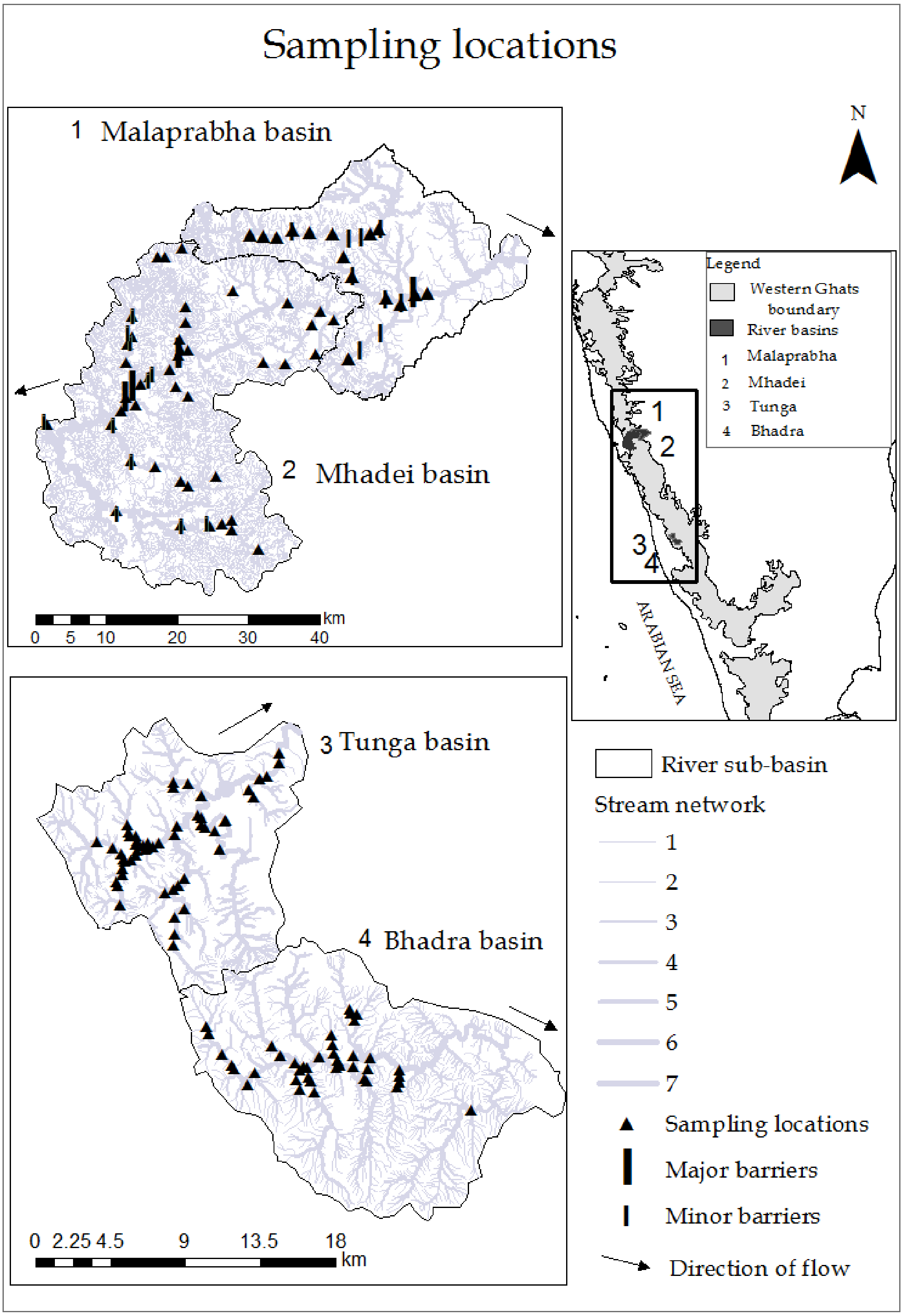

Figure 2. 1. (a) Sampling locations in the four river sub-basins of the Western Ghats, India (b) Malaprabha-Mhadei (c) Tunga-Bhadra

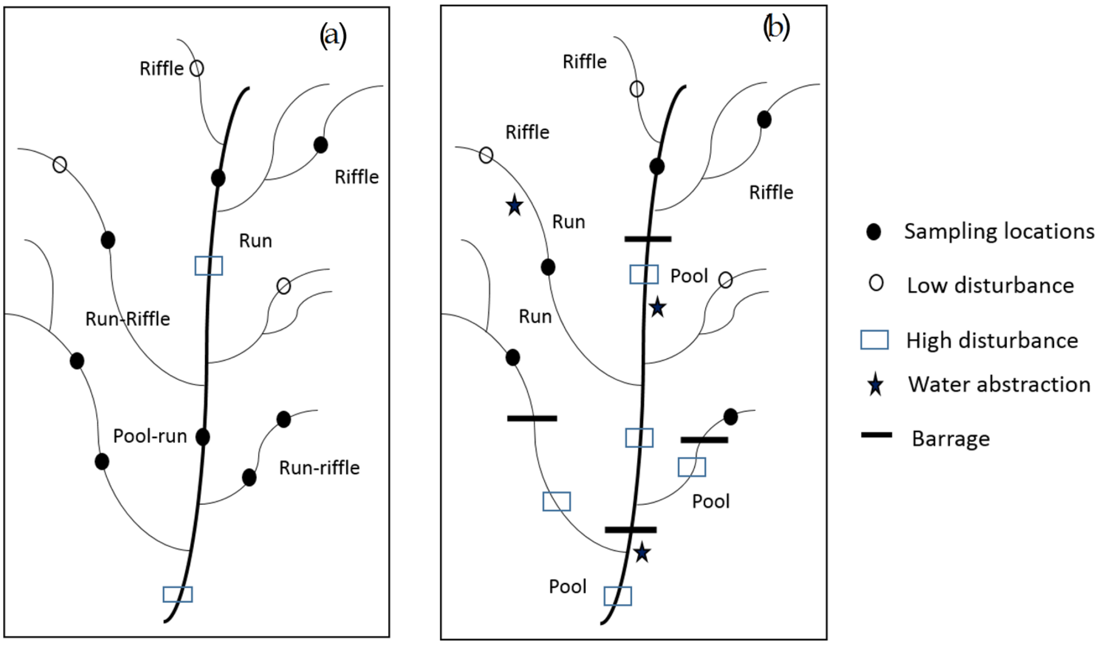

Figure 2. 1 (d)**.** Schematic diagram showing a nested sampling design. Figure on left indicates relatively undisturbed river systems and figure on right shows relatively more disturbed river system.

-standing demand to divert water from these tributaries via an inter-basin transfer project to the Malaprabha river. The northern part of the basin is largely dominated by moist deciduous and evergreen forest while the southern part consists largely of agriculture and plantation. Water quality is affected by effluent from domestic water uses and disposal of untreated sewage. In addition, water abstraction for irrigation, agriculture and other domestic use is affecting river health. I classified Mhadei as another regulated sub-basin.

The other two river basins, (3) Bhadra and (4) Tunga, originate at an elevation of 1160 m near in the WG Gangamoola hill range in the Kudremukh National Park in the Chikkamgaluru and Dakshin Kannada districts of Karnataka state. The park is one of the UNESCO world heritage sites in the WG, dominated by wet evergreen forest and shola grassland (Kasturirangan, 2013). Each river is fed by numerous small to medium-sized perennial streams. I identified nine major streams in Bhadra and ten major streams in Tunga sub-basin. Water quality is not severely affected by various anthropogenic pressure. Bhadra drains into Bhadra reservoir situated at 142 km from Gangamoola. Tunga joins Bhadra downstream, thereby becoming the Tungabhadra river. Subsequently, it joins river Krishna at Kudalsangama in the Bagalkot district of

Karnataka state and finally meets the Bay of Bengal. (Fig. 2.1). Detail of each river basin is given in Table 2.1 a-c.

Sampling strategy

I delineated the catchment area for each river sub-basin using Geographic Information System tools (ArcMap 10.1, Table 2.1a and b). I followed nested sampling design wherein each sample consisted of a river segment of approximately 100-150 m length. A segment consisted of a set of one or multiple channel units or meso-habitats including run, pools, runs, riffles and a cascade or a sequence of pool-run, run-riffle and riffle-pool. These segments were situated in different stream orders (1-7) in a sub-basin. I sampled such segments from the headstream to downstream (Table 2.1a, Fig. 2.1d). Systematic sampling was undertaken during different seasons. The total number of samples as per the nested sampling design in different seasons are as shown in Table 2.1c.

Table 2. 1a details of sampling locations in each of the river basin.

River basin/Streams	Seg. name	Elevation (m)	Stream order	No of seg.
(1) Bhadra sub-basin				
Bhadra	Kadambi joint	829	3	13
	Bh7	860	3	
	Oldgrass point	854	3	
	Kurinjikal	830	3	
	Khasigadde	834	3	
	Bhagvati	825	4	
	Pandarmakki road	824	4	
	Bh-kachige joint	778	4	
	Khagundi	761	5	
	KIOCL	770	5	
	Nagraj mane	760	5	
	Kudremukh bridge	755	5	
	Hosmakki joint	750	5	
Biligal	Biligal1	775	4	03
	Biligal3	805	3	
	Biligal5	816	3	
Kachige	Kachige1	778	4	04
	Kachige3	785	4	
	Kachige4	790	4	
	Kachige5	806	4	
Singsar	Singsar1	810	4	03
	Singsar2	814	4	
	Singsar3	928	4	

River basin/Streams	Seg. name	Elevation (m)	Stream order	No of seg.
Kunya	Kunya1	780	3	05
	Kunya2	782	3	
	Kunya3	795	3	
	Kunya4	824	3	
	Kunya5	829	4	
Carman	Carman1	795	4	04
	Carman2	810	4	
	Carman3	814	3	
	Carman4	898	3	
Hosmakki	Hosmakki1	910	1	03
	Hosmakki2	920	4	
	Hosmakki3	930	4	
Nelibedu	Hosmakki4	767	3	03
	Nelibedu1	802	3	
	Nelibedu3	809	3	
	Nelibedu5	861	3	
Somvati	Somvati1	1053	2	02
	Somvati2	802	3	
(2) Tunga sub-basin				
Mudba	Mudba1	664	4	05
	Mudba2	670	4	
	Mudba4	675	4	
	Mudba5	700	3	
	Mudba8	700	3	
Mundsar	Mundsar1	652	4	04
	Mundsar2	667	4	
	Mundsar4	675	4	
	Mundsar8	700	4	
Turad	Turad1	642	4	04
	Turad2	689	4	
	Turad3	690	4	
	Turad4	754	4	
Karuchar	Karuchar1	667	4	06
	Karuchar2	672	4	
	Karuchar3	686	4	
	Karuchar4	691	4	
	Karuchar5	693	4	
	Karuchar6	697	4	
Korkan	Korkan1	656	4	06
	Korkan2	661	4	
	Korkan3	675	4	
	Korkan4	676	4	
	Korkan6	679	4	
	Korkan11	880	4	
Gangehole	Ghole2	776	3	04
	Ghole4	773	4	
	Ghole6	716	4	
	Ghole8	698	3	

River basin/Streams	Seg. name	Elevation (m)	Stream order	No of seg.
Muje	Muje3	662	3	03
	Muje4	667	3	
	Muje7	680	4	
Tanikod	Tanikod2	736	2	02
	Tanikod4	811	2	
Vimala	Mudba-mundsar joint	761	4	08
	Tn2	681	5	
	Acharmakk	677	5	
	Tumbahalla	673	5	
	Before Acharmakki	670	5	
	Keshav mane	667	5	
	Before Kerekatte1	665	5	
	Before Kerekatte2	665	5	
Tunga	Kerekatte	656	5	11
	Kerekatte school	655	5	
	Trogen point	650	5	
	Before Anand mane	650	5	
	Anand mane	650	5	
	Yadgar	650	5	
	Muje joint	645	6	
	Tanikod joint	645	6	
	Toursit point	635	6	
	Salmara	630	6	
	Nemmar	630	6	
(3) Malaprabha sub-basin				
Haltar nala	Shiroli	672	4	02
	Shedegali	650	4	
Mangetri nala	Katgali	713	4	02
	Valmiki	700	4	
Malaprabha	Amta	720	3	11
	Torali	715	3	
	Devachihatti	720	3	
	Habbanhatti	714	3	
	Kusmali	700	3	
	Malavi	711	3	
	Olmani	693	3	
	Shankerpeti	653	4	
	Asoga	643	4	
	Rumewadi	655	5	
	Kupatgiri	650	5	
(4) Mhadei sub-basin				
Mhadei	Degaon	685	3	12
	Before Kongla	635	5	
	Kongla	627	4	02
	Kotni	610	4	02
	Below Kishnapur	48	6	
	Ustem	44	6	

River basin/Streams	Seg. name	Elevation (m)	Stream order	No of seg.
	Ustem 2	44	6	
	Sonal	41	6	
	Cudcem	31	6	
	Velgeum	27	6	
	Khadaki	18	6	
	Khotode	14	6	
	Waghurme	14	7	
	Jamgaon	673	4	
Bhandura	Nerse	650	4	
Panshet nala	Talewadi	760	3	01
Bail nadi	Bail nadi	721	3	01
Kalasa	Satrem	112	3	06
	Derodem	84	4	
	Nanodem	62	4	
	Kankumbi	750	3	
	Delta hotel	694	3	
	Checkpost	733	3	
Kotryachi nadi	Thane	85	5	04
	Hedode	79	5	
	Naneli	65	5	
	Velus	49	5	
Patwal	Patwal	12	4	01
Ragada	Vasant bandhara	135	1	06
	Jambolim	21	4	
	Satpali	61	4	
	Panas	32	4	
	Shivade	16	4	
	Murmune	13	5	
Dudhsagar	Dudhsagar fall	146	4	06
	Devachi kon	97	4	
	Dudhsagar juntion.	85	4	
	Cullem	74	5	
	Shigaon	58	5	
	Dabal	22	5	
Caranzhol	Cumtol 1	104	3	02
	Cumtol 2	50	4	
Karanjhol	Karanjhol	83	4	01

Table 2. 1b details of catchment area, direction of flow and the state in which the study is conducted (KN – Karnataka)

River Sub-basin	Headwater elevation (m)	Downstream elevation (m)	Catchment area (km^2)	Direction of flow	State
Mhadei	610-760	10 - 150	1332.02	West	KN, Goa
Malaprabha	640-720	-	0744.32	East	KN
Bhadra	750-930	-	225.12	East	KN
Tunga	630-880	-	160.00	East	KN

Table 2. 1c sampling duration in each of the river sub-basin.

Basin	Duration of sampling	Season	Method	Mesh size (cm)
Bhadra	May 2013	Dry	Castnet	0.5 x 0.5, 1.1 x 1.1
	June 2012, Nov- Dec 2013	Wet	Castnet	0.5 x 0.5, 1.1 x 1.1
Tunga	May 2013	Dry	Castnet	0.5 x 0.5, 1.1 x 1.1
	June 2012, June 2013, Dec 2013	Wet	Castnet	0.5 x 0.5, 1.1 x 1.1
Malap.	Apr 2011, Mar 2012, May 2014	Dry	Castnet	0.5 x 0.5, 1.1 x 1.1
	June 2011, Jan 2014	Wet	Castnet	0.5 x 0.5, 1.1 x 1.1
Mhadei	March 2012, April 2012, April 2013, May 2014	Dry	Castnet	0.5 x 0.5, 1.1 x 1.1
	June 2011, Jan 2014, Feb 2014	Wet	Castnet	0.5 x 0.5, 1.1 x 1.1

Fish sampling

Fish sampling was conducted with the help of cast net (0.5 cm x 0.5 cm and 1.1 cm x 1.1 cm mesh size). I relied on using a cast net over other fishing methods (gillnet and electrofishing etc) for the following reasons. First, it is a non-destructive fishing technique with the least fish mortality and is widely used in the tropical countries. It has been shown to capture most of the fish species present in a river habitat (Abraham and Kelkar 2012; Bhat, 2002) and can be operated by a single person with high sampling efficiency. It is also easily portable and enables more sampling points and locations. Most of the sampling segments were located in the deeper and undulating parts of the protected area which were only accessible by foot. A segment was sampled thoroughly with 18 casts for approximately 120 minutes to ensure that the catch represents most of the functional fish guilds including surface dwellers, mid-column dweller and bottom dwellers. I calculated fish sampling effort within stream segments (which included one or more mesohabitat units i.e. pool, run, riffle). These mesohabitat units were visually distinguished as areas for fish sampling as run consist of areas of stream stretches with gentle or fast water velocity with shallow depth, riffles as fast flowing water with turbulence due to submerged gravels and pebbles, pools are the areas with little or no water velocity and cascades are short waterfalls (Bhat, 2003; Hauer and Lamberti, 2007). Therefore the data collected in each mesohabitat unit was run (n=74), riffle (n=26), pool (n=51). Individuals of each fish were identified to the species level, measured (total length in cm) and released at the collected sites. Only unidentified individuals (1-2 per morpho-species) were collected, preserved in 90 % ethanol and subsequently transferred into 70 % ethanol in the laboratory for further identification. Standard textbooks following taxonomic key were used to identify species (Day, 1875; Daniels, 2002; Jayaram, 2010). Fish taxonomists and fish biologists were also consulted for species identification, especially for some of the complex groups of fishes.

Habitat variables

Data on habitat characteristics at each sampling segment were collected following the fish sampling. These included measurement of river width (m), river depth (m) three readings along the stream width, water temperature (^{0}C), electrical conductivity (µS/cm), total dissolved solids (ppt), pH, canopy cover (%), and substratum (%). Portable water tracers were used to record electrical conductivity (Hanna Instruments HI98302), total dissolved solids (HI98304) and pH (HI96107). A water sample was also collected from the mid-section of each segment for the estimation of other water quality parameters in the laboratory including total hardness (mg/l), calcium hardness (mg/l), free CO_2 (mg/l), chlorides (mg/l), total alkalinity (mg/l), inorganic nitrates (mg/l) and inorganic phosphates (mg/l). All these samples were analyzed in the laboratory within 24-48 hrs. Water analysis was performed by following standard protocols (APHA, 2005; Trivedi and Goel, 1986). River bed substratum was visually categorized into proportions of rocks, boulders, sand, gravel and mud, leaves and wood. Canopy cover (%) was also visually estimated at each segment. Presence of riparian vegetation (dominant tree and shrubs and weeds) was noted. Previously sampled segments were re-sampled during a different season from the reverse direction to remove artefacts of direction of sampling.

Statistical Analysis

In total, I sampled fish from 152 segments in 33 streams in four sub-basins to determine patterns of fish community organization. I calculated fish species diversity (richness and abundance) in each of the sampled segments. Species richness, the number of species recorded in each segment, was calculated based on species accumulation curves across four sub-basins and the number of individuals. Overall rank abundance was also calculated to examine the dominant species in the study area. All calculations were carried out in R statistic (R Development Core Team, 2011) using the package BiodiversityR (version 2.5-1). Generalized Linear Models (GLMs) were used to evaluate the relative influence of environmental drivers such as stream characteristics and water quality variables on fish richness and fish abundance.

I checked multicollinearity in predictor variables by calculating the variance inflation factor (VIF). VIF quantifies inflation in parameter estimates due to multicollinearity (Guisan et al., 2002). Variables that contributed to high variance were removed and those with VIF less than three were retained (Ott and Longneck, 2010). Model selection procedure based on AIC criteria was then used as a measure of information loss of each candidate model, with the best fitting model having the lowest AIC value (Crawley, 2007). I noted disturbance level in each of the sampled segments to test the effect of disturbance on species richness and abundance. Broadly, I defined a disturbance as any event that directly/indirectly affects fish diversity (richness and abundance). A level of 'high disturbance' was assigned to segments that exhibited either fishing pressure, sand-boulder mining, dynamiting, presence of pollution, presence of check dam or any hydrological barrier, medium disturbance to segment with water extraction for plantations, combined activities washing, bathing & vehicle washing, water diversion for hotel use, etc and 'low disturbance' to segments that lacked any significant level of disturbance but includes washing & bathing, livestock washing, vehicle washing, water extraction for drinking purpose (Appendix -1). Based on the intensity of disturbance and its likely impact on fish fauna, I ranked disturbance on a scale of 1 to 12, with low (1-4), medium (5-8) and high (9-12) disturbance rank.

Results

Patterns in fish diversity (between river sub-basin and seasons)

Fish species diversity assessed in four sub-basins revealed a total of 93 species belonging to nine orders and 18 families with 18,322 individuals. The order *Cypriniformes* was the richest (93% of the total orders) with 27 generas and 60 species followed by the orders *Siluriformes* and *Perciformes* (each with 6 genera and 13 species family *Cyprinidae* dominates among all families with 49 species followed by *Balitoridae* with 10 species and Cobitidae (1 species), (Appendix – Ib).

The cumulative species richness for the segments varies in each river sub-basin (Fig. 2. 2a). When the species richness of segments was compared, Malaprabha basin showed the highest observed species richness. For this basin, the species accumulation curve (SAC) did not reach an asymptote when the data for 15 segments were added, suggesting that Malaprabha is a hyper diverse basin. Mhadei was the second most species rich basin, with the SAC stabilizing around forty species. The Tunga sub-basin also showed a similar trend, reaching an asymptote around 40 species. The Bhadra sub-basin, reached an asymptote quite early, and the species richness was estimated to be around 20. Malaprabha river sub-basin showed highest species richness (53 species in 15 sites) followed by Mhadei (47 species in 32 sites), Tunga (45 species in 52 sites) and Bhadra (24 Species in 41 sites), (Fig. 2. 2a). The cumulative species richness sampled across total number of individuals showed an interesting pattern. The maximum number of individuals were caught in Mhadei (7335) sub-basin alone, followed by Tunga (4447), Malaprabha sub-basin (4050) and Bhadra (2489) (Fig. 2b). The lower detection probabilities in capturing fish species richness and individual encounter rate using cast net has likely resulted in this variation in species richness and abundance.

My analyses also shows that wet season richness reached its asymptote earlier than the dry species richness (Fig. 2. 2c and d). The individual accumulation curves are also shown in Fig. 2. 2b and for the wet and dry season in Fig. 2. 2d. Species abundance in both dry and wet seasons accumulated steadily when more than 10,000 individuals were caught in the four sub-basins (Fig. 2. 2d).

Among all fishes, the five most abundant species belong to the family Cyprinidae, and include *Devario malabaricus*, *Salmophasia boopis*, *Garra mullya*, *Rasbora daniconius* and *Barilius bakeri* (Fig. 3a, b and Appendix -III). This family is by far the most abundant in the rivers of this region. Similar results were found for each of the river basins (Appendix III). Mhadei basin showed the highest fish abundance followed by Malaprabha, Bhadra and Tunga.

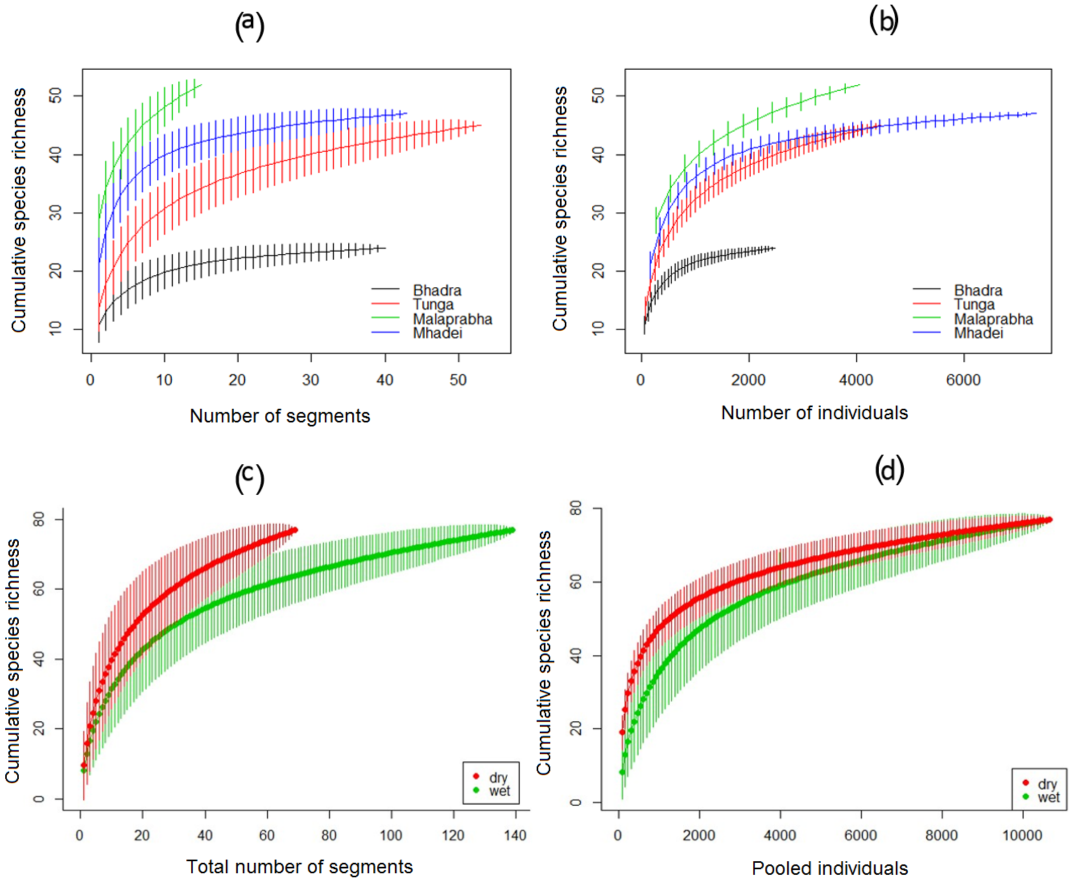

Figure 2. 2 (a). The species accumulation curve for each river sub-basin (b) species accumulation curve across number of individuals, (c) The species accumulation curve for dry and wet season using number of segments sampled and (d) pooled individuals from all the sampled segments.

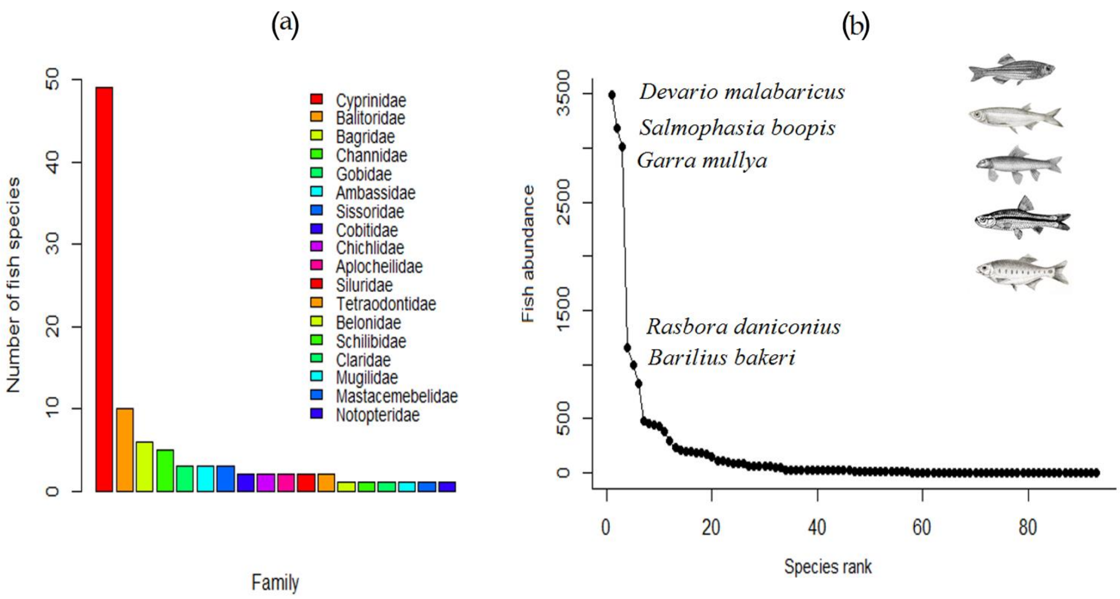

Figure 2. 3 (a) dominant fish families (b) species abundance rank distribution showing five dominant fish species across four river sub-basins.

I also observed a hump-shaped relationship between the mean richness and mean abundance as a function of stream order (Table 2.1 d and 2.1 e; Fig. 2. 4a and b).

Table 2.1 d. Fish richness with mean, SD and SE across stream order

Stream Order	No of segments	Fish richness	Mean fish richness	SE (SE)
1	2	2	0.143	0.34 (0.18)
2	3	3	0.215	0.42 (0.14)
3	39	10	0.715	0.46 (0.01)
4	49	9	0.643	0.49 (0.01)
5	11	11	0.786	0.42 (0.03)
6	8	11	0.786	0.42 (0.05)
7	1	2	0.143	0.36 (0.36)

Table 2.1 e. Fish abundance with mean, SD and SE across stream order

Stream Order	No of segments	Fish abundance	Mean fish abundance	SE (SE)
1	2	23	0.248	1.04 (0.52)
2	3	141	1.516	8.15 (2.71)
3	39	4268	45.893	156.12 (4.004)
4	49	7901	84.957	276.32 (5.63)
5	11	4112	44.216	135.87 (12.35)
6	8	1827	19.646	60.93 (7.61)
7	1	50	0.538	2.65 (2.65)

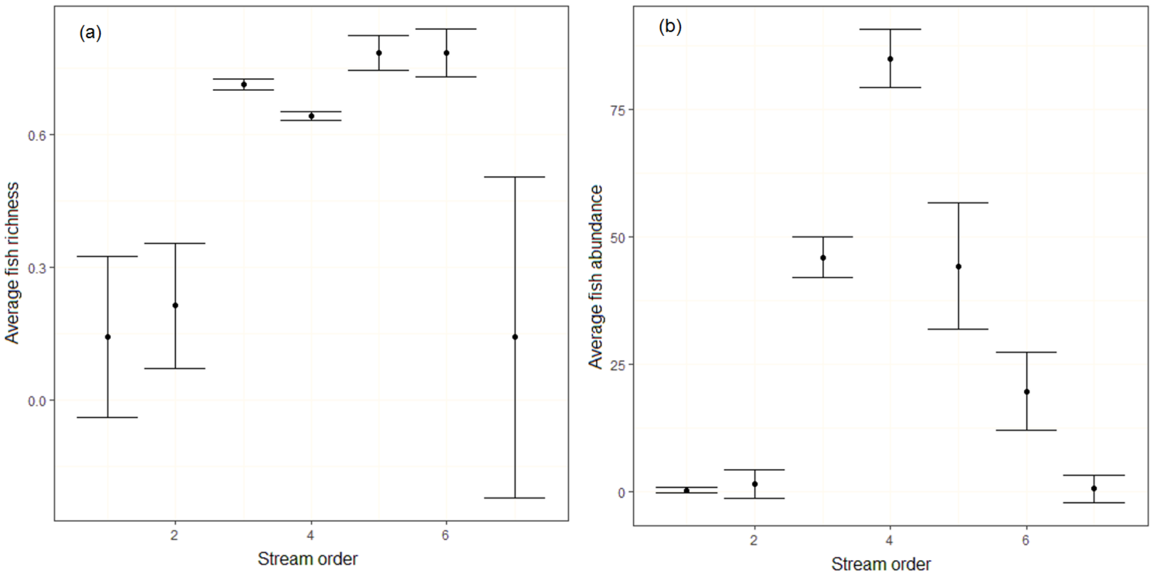

Figure 2. 4. (a). The relationship between average fish species richness and stream orders (b) average species abundance and stream order.

The frequency distribution suggests that most species were rare while very a few species were abundant. Endemic species richness was higher in the middle stream orders especially in Tunga Mhadei and Bhadra compared to Malaprabha. Relatively sample size was less Malaprabha than other river sub-basins (Fig. 2.5).

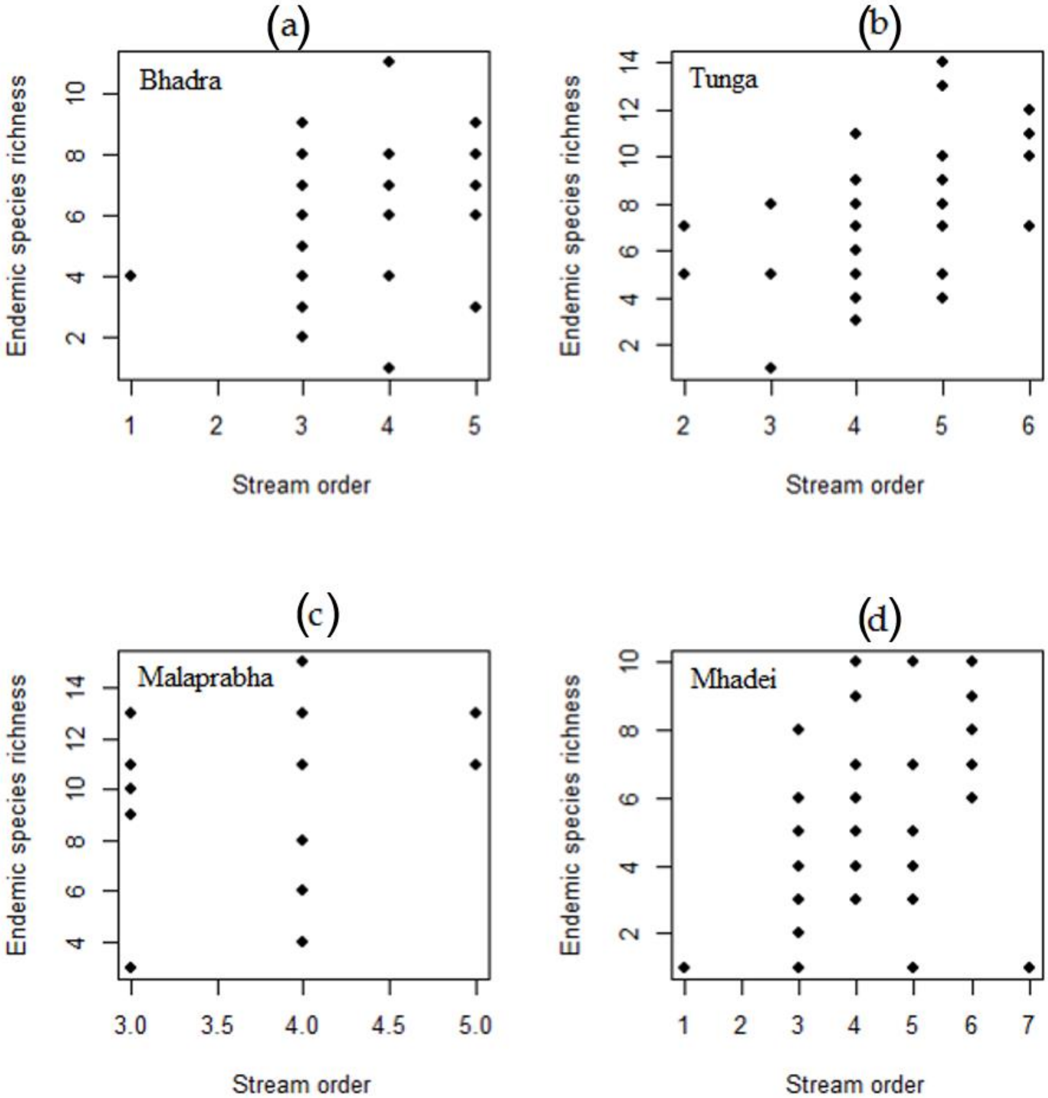

Figure 2. 5. Endemic species richness in different stream orders (a) Bhadra (b) Tunga (c) Malaprabha (d) Mhadei.

Fish diversity (richness-abundance) and habitat variables

The best model from GLMs showed that species richness was positively correlated with water temperature, free CO_2, rocks and, gravels and negatively correlated with disturbance level, depth width ratio, boulders, cobbles, pebbles, sand, calcium hardness, inorganic nitrates and dissolved oxygen (Pseudo R^2 = 0.55). Similarly, fish abundance was positively correlated with dissolved oxygen, depth-width ratio, rocks, gravels, water temperature and free CO_2 and negatively correlated with disturbance level, inorganic nitrates, calcium hardness, boulders, pebbles, and sand, respectively (Pseudo $R^2 = 0.59$), (Table 2.2).

Table 2.2. Parameter estimates for fish species richness and fish species abundance.

Response	Coefficient	Estimate (SE)	CI (2.5%)	CI (97.5%)	Pseudo R^2	AICc
Fish richness	(Intercept) ***	3.76 (0.68)	2.42	5.07	0.55	378.68
	Disturbance Low***	-0.71 (0.13)	-0.97	-0.45		
	Disturbance Med***	-0.33 (0.10)	-0.52	-0.13		
	Free CO_2**	0.006 (0.002)	-0.001	0.010		
	Calcium hardness	-0.001 (0.0008)	-0.002	0.0005		
	Inorganic nitrates	-0.23 (0.19)	-0.62	0.14		
	Dissolved oxygen*	-0.04 (0.02)	0.004	0.09		
	Depth width ratio	-2.68 (1.66)	-5.97	0.54		
	Water temperature*	-0.05 (0.02)	-0.11	-0.001		
	Electric conductivity***	6.74 (1.98)	2.83	10.60		
	Rocks	-0.0005 (0.003)	-0.007	0.006		
	Boulders.	-0.005 (0.003)	-0.013	0.0009		
	Cobbles	-0.04 (0.004)	-0.013	0.005		
	Pebbles	0.001 (0.004)	-0.006	0.010		
	Gravels	0.0004 (0.003)	-0.005	0.006		
	Sand**	-0.01 (0.004)	-0.02	-0.003		
Fish abundance	Intercept***	4.34 (0.17)	4.00	4.67	0.59	3234.5
	Stream order***	-0.08 (0.01)	-0.11	-0.06		
	Disturbance Low***	-1.61 (0.03)	-1.68	-1.54		
	Disturbance Med***	-0.77 (0.02)	-0.82	-0.72		
	Free CO_2***	0.01 (0.0007)	0.008	0.01		
	Chloride***	-0.004 (0.0004)	-0.005	-0.003		
	Calcium hardness***	-0.001 (0.0002)	-0.001	-0.001		
	Inorganic nitrates***	-0.19 (0.05)	-0.300	-0.086		
	Dissolved oxygen***	0.02 (0.005)	0.01	0.03		
	Depth width ratio***	5.26 (0.42)	4.42	6.10		
	Water temperature***	0.04 (0.006)	0.03	0.059		
	Rocks***	0.01 (0.0009)	0.011	0.015		

Boulders***	-0.01 (0.001)	-0.01	-0.01
Pebbles***	-0.008 (0.001)	-0.01	-0.006
Gravels***	0.01 (0.001)	0.01	0.014
Sand***	-0.01 (0.001)	-0.01	-0.009

Statistical significance (alpha = 0.05), p values * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Fish species richness was highest in the pool habitat followed by riffle and run (Fig. 2.6a). Fish abundance was highest in pool habitat followed by run and riffle (Fig. 2.6 b). One-way Analysis of Variance (ANOVA) was used to test the difference in variation in fish richness and fish abundance across major habitat types. Tukey's test was used for post hoc comparison between different habitat types. However, there was no statistical difference in any of the habitat types.

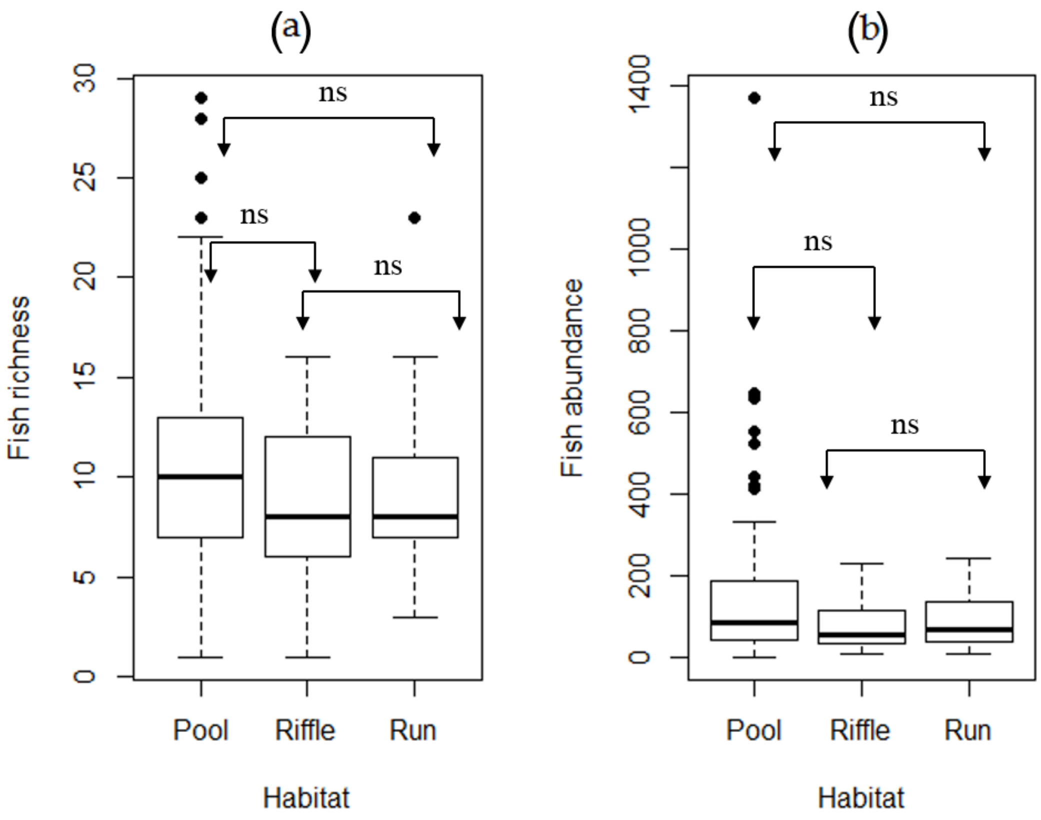

Figure 2.6. Fish species richness (a) and abundance (b) across three habitat types.

Fish diversity (richness-abundance) and disturbance relationship

About 13 of the segments in my data were classified as highly ('more') disturbed, and 139 were classified as least ('less') disturbed. My results demonstrate that streams with more disturbance were associated with higher species richness and the less disturbed segments showed greater fish abundance (Fig. 2.7a and b). ANOVA suggest that there was significant difference in the disturbance level both for richness (p =0.003) and abundance (p=0.07).

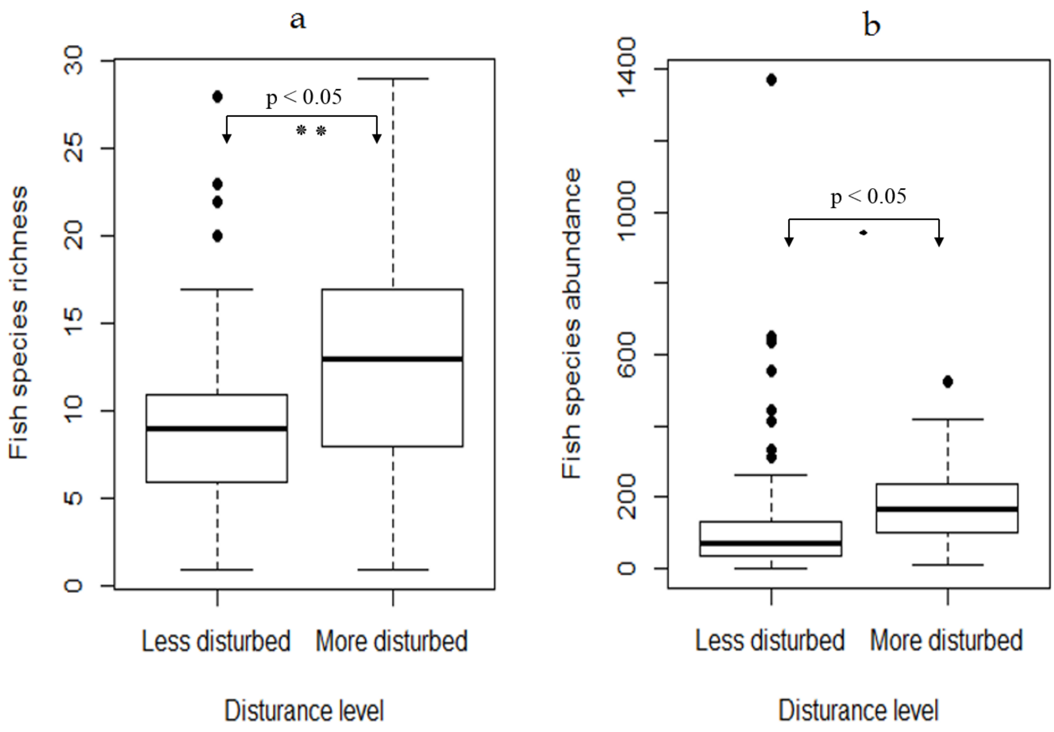

Figure 2.7 (a) Species richness and abundance (b) across disturbance levels.

Discussion

Taxonomic richness (order, family, genera and species)

This study provides a systematic examination of freshwater fish communities at different spatial scales (segment, habitat, stream order and sub-basins) within and across river sub-basins in the WG, thus enabling a comprehensive understanding of fish community organization. My results demonstrate that at large spatial scales, river size (sub-basin as well as stream orders) governed species richness (Fig. 2.2) and at local scales (segment level), stream characteristics and water quality variables predicted species richness and abundance (Table 2.2). Generally, water quality in the regulated sub-basins (Malaprabha and Mhadei) was degraded due to a variety of anthropogenic factors including land use patterns. In spite of this, these regulated sub-basins showed higher species richness than unregulated sub-basins (Bhadra and Tunga) where the "water quality" was better. The high richness observed in Malaprabha sub-basin could be primarily due to the presence of lentic habitat (pools) which are relatively more stable (due to the impoundment effect) than the run and riffle habitats. The other possible reason for highest species richness in Malaprabha could be connectivity of other upstream habitats in the river with the back-waters of the Saundatti dam which has mitigated to some extent the decline in the discharge of the river. The next highest richness in the Mhadei and Tunga sub-basin could be attributed to the dense stream network yielding diverse river habitats and abundant food resource in the form of macro-invertebrate diversity (Subramanian et al., 2005; Ibrahampurkar, 2012). The higher richness of endemics found in the Tunga and Malaprabha basins could be due to the geomorphology and dense stream network that generates a diverse set of stream habitats that are also less disturbed from anthropogenic disturbances (Fig. 2.5).

Drivers of species diversity

Results of the generalized linear models suggest that species richness was predicted by stream related variables and water quality parameters, a pattern commonly documented in stream fish ecology (Gido and Jackson, 2010; Matthews, 1998). Higher levels of calcium hardness and reduction in canopy cover negatively influenced fish richness while free CO_2 and water temperature influenced richness positively. A higher amount of free CO_2 (> 50 mg/l) was present in stagnated pools especially in Malaprabha and Mhadei. Bhadra and Tunga had relatively more runs and riffles which were higher in dissolved oxygen. Water temperature has a significant effect on aquatic life through its effect on metabolism (Chapman, 1996; Dallas, 2008). In this study, increase in water temperature was perhaps due to 1) the effect of dam (Lessard and Hayes, 2003) as higher water abstraction would have reduced flow downstream leading to shallower and disconnected pools, and 2) lack of adequate riparian vegetation cover especially along the regulated sections of rivers (Malaprabha and Mhadei).

The water chemistry in terms of its hardness and alkalinity has changed and these variables show increased levels at a few segments due to washing, bathing, and vehicle washing (Table 2) which might affect osmoregulation in fish making them become vulnerable to infectious diseases and thus increasing mortality (Trivedi and Goel, 1986; Chapman, 1996). The other reason for rise in calcium hardness level in regulated river sub-basin, could be the combined effect of water abstraction and hydrological barriers by reducing the ratio of surface to ground water immediately downstream of flow (Wurts and Robert, 1992; Merz, 2013; Atkore et al., 2017). As a result, water column dependent positional guilds seem to have been affected (Atkore et al., in Prep). However, the diverse responses of diverse fish guild is difficult to assess to pinpoint the tolerance level of key fish groups. Future studies should focus on specific responses of these groups to different environmental factors.

Analyses of the temporal patterns also suggested that fish communities showed seasonality in their richness and abundance. Higher fish richness was found in the dry season especially in the pool habitats, which were a dominant feature of large rivers such as Malaprabha, Mhadei and Tunga (Fig. 2.6). The water abstraction at fewer sampled sites in Malaprabha river could have reduced the water depth forcing most fishes to congregate at such habitats during dry season. The findings of this study correspond with studies elsewhere where authors attributed the higher dry seasonal richness to the habitat loss, higher evaporation but not due to change in the water quality in selected river segments (Arthington et al., 2005). In my study, more disturbed segments had higher species richness. This may be because segments with more disturbance were dominated by pool habitats rather than run and riffle habitats. However, fish abundance was higher in less disturbed segments (with runs/riffles) suggesting these sites were occupied by fry and juveniles, especially during wet season.

This was partly confirmed in an exploratory analysis which indicated that the body size of dominant fishes in the regulated sub-basins was relatively larger (>12 cm) than non-regulated segments (Appendix III, Fig. 2. 4 and 2.5). These fishes and other bigger barbs (*Hypselobarbus* sp, *Tor* sp) in the regulated basins were exposed to higher fishing pressure (dynamite use and diverting or stopping water and agricultural/ town sewage) compared to the non-regulated river basins. As a result, many fishes (15-20 individuals) including a few endemic species (*Osteochilius nashii* and *Labeo fimbriatus*) showed signs of disease and deformities. Previous studies focusing on disturbance have shown mixed results with respect to richness and abundance in disturbed tropical streams (Kondoh, 2001; Dornelas, 2010; Deacon et al., 2015). When considering the impact of disturbance on fish communities, researchers found that natural and unimpacted rivers had more structured or nonrandom species distribution than rivers with disturbance (Bhat and Magurran, 2007). A study conducted in the southern WG has shown that, higher degree of fish endemism was restricted to the mid-elevational zones that occur within protected area boundaries (Abraham and Kelkar, 2012). Such studies are becoming more important and question the efficacy of the current terrestrial protected area approach for conserving riverine biodiversity. The present study also corroborates these findings demonstrating that endemic fish richness was restricted to the middle stream orders which are mainly found in the non-regulated river systems. Habitat complexity was diverse in the Bhadra and Tunga sub-basins due to the presence of pool, run, riffle and cascades which provided suitable breeding ground for most of the macroinvertebrates (Subramanian et al., 2005). It is important to maintain adequate connectivity between the main and different stream orders (especially outside the protected area boundaries) that allow migratory fishes to make use of shallow, diverse habitats that are well oxygenated for spawning and feeding. The location of many hydrologic barriers in the middle stream orders is thus a major threat to the fish diversity of the WG. Thus, this study fills an important knowledge gap on the fish communities of the relatively less studied but diverse river systems of the central WG region.

Basin biogeography

Among the studied river basins, three rivers were east flowing (Malaprabha, Bhadra and Tunga) and one river was west flowing (Mhadei) and these differences in flow may also account for differences in species richness as the catchments on either side of the WG differ in key biophysical characteristics. West flowing rivers are geologically young, have short courses with high gradient less sediment load, high water velocity, less catchment area (species-area effect), and lack an extensive network of tributaries compared to the east flowing rivers (Gunnell and Radhakrishnan, 2001). The steeper elevation gradient gives rise to numerous falls, cascades, and rapids which harbors rich endemic fish fauna (Mani, 1974; Johnson and Arunachalam, 2009) in west flowing rivers. The other factors that would have resulted in the variation in species richness are catchment size, channel morphology, land use history and basin biogeography. The channel morphology, especially substrate composition, in east and west flowing rivers in the headwater region was similar i.e. largely dominated by rocks, boulders, pebbles, gravels (making a suitable niche for habitat specialist and endemic fishes) (Mani, 1974) but this composition reduced significantly at downstream sections which was dominated largely by sand and silt with more general and favoring widely distributed fish species.

Biogeographically, a few species were exclusively endemic to one or two river basins. For instance, the genera *Barilius*, *Barbodes* were restricted only to the Bhadra and Tunga river basins but were not found in the Malaprabha and Mhadei river basins. Similarly, certain species such as *Glossogobius* sp and *Mugil* sp were estuarine forms restricted only to the Mhadei river basin and not found in other river basins. Species such as *Sicyopterus* was also restricted to the upper reaches of Mhadei not found in the other study segments. Many large body-sized endemic species (*Hypselobarbus dobsoni*, *H. thomassi*, etc) were found only in the relatively disturbed segments during the monsoon season, in the Malaprabha river. Some of the relatively disturbed river segments (Katgali, Asoga and Rumewadi) in Malaprabha harbor potentially new species which indicates such areas need more conservation attention in terms of detailed species inventories. Many migratory species (eurytopic) fishes were captured in this river basin alone. Many of them are tolerant to wide disturbance regime.

Water sharing from one basin to other has been a contentious issue, especially when the rivers run between two or more states. For instance, Karnataka and Goa states are involved in a water sharing disputes over the waters of Mhadei and Malaprabha. Additionally, within the state of Karnataka, in order to meet drinking water needs of multiple cities, there is a plan to divert the headwater from Mhadei upstream tributaries (which is within the state) to the main Malaprabha river via an irrigation canal. This has elicited wide protests and conflicts already (http://indiatoday.intoday.in/story/river-dispute-karnataka-and-goa-headed-for-a-major-clash/1/461596.html). Further, many headstream sites in the basin have been demarcated for constructing new dams or barrages in the near future. Abstraction by irrigation canals in the past have already destroyed the habitats of many specialist fish species. Once this new canal becomes functional, it might homogenize habitats and associated fish assemblages across two basins, affecting endangering numerous habitat specialist, and endemic fish species.

Conservation status and endemism

In terms of IUCN threat status (Molur et al., 2011), 16 species have not been evaluated in the conservation status report (Molur et al., 2011) simply due to lack of information from this region (see Appendix- I). In addition, of the species reported in the study, 8 species were classified as Endangered, 3 were Vulnerable and 2 were Near Threatened, 2 were critically endangered, 4 were Data Deficient and 58 were classified as Least Concern. This study describe a new fish species of *Pethia striata* from the study region (Atkore et al., 2015) and also reports a healthy population of the Critically Endangered fish species i.e. *Barbodes wynaadensis* and the presence of *Hypselobarbus thomassi*, a new distributional record for *Labeo dussumieri* filling an important knowledge gap in Indian fish taxonomy. Of the 93 species, about 52 species are endemic to the WG region and about 40 are non-endemic, but native to the Indian subcontinent.

Mhadei and Malaprabha showed a greater degree of disturbance that has led to the destruction of natural river substratum, making segments deeper and dominated by sand, and agricultural sewage. In the case of Bhadra and Tunga, such instances of higher levels of disturbances are rare but they show a higher proportion of non-forest land cover, especially, plantations and agriculture. Additionally, water quality at certain segments was degraded due to washing activities, which might affect the fish population indirectly. In terms of river management, priority should be given to maintaining adequate connectivity between the main river channel and its distributaries. The types of disturbance that directly affect fish population should be regulated and effective ways of engaging local communities for river conservation should be promoted. Monitoring as well as conservation efforts should focus more on assessing endemic species diversity and community composition.

To conclude, this chapter demonstrates the importance of the four river basins (Mhadei, Malaprabha, Tunga and Bhadra) for fish diversity in the WGs. Malaprabha and Mhadei showed higher species richness, despite being regulated streams. However, abundance was higher in these non-regulated rivers including the Tunga basin. My results suggest that fish diversity including that of endemics is higher in large rivers with intact middle stream orders and the overall community structure is shaped by stream characteristics and water quality variables.

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Chapter 3

Determinants of native fish species turnover in the Western Ghats, India

Introduction

Biodiversity at the global scales is concentrated in tropical regions but determining drivers of diversity for specific groups within the tropics is an area of active investigation (Arthington et al., 2010; Vorosmarty et al., 2010; Boyero et al., 2011; Dudgeon, 2011; McGill et al., 2015). However, little is known about how biodiversity, especially, fish communities change along an environmental gradient. This is interesting both from a biogeographical perspective, as it offers insights into the mechanisms by which species are accumulated (nestedness, turnover, colonization, extinction etc) and from the perspective of understanding the effect of river regulation due to dams and other water diversion schemes. Community change across environmental gradients has been understood by assessing species turnover by using beta diversity measures (Magurran, 2004; Alfonsi et al., 2016).

Whittaker (1960) made the distinction between α- and β-diversity. He defined α-diversity as the property of a defined spatial unit, while β-diversity reflects biotic change or species replacement as from one spatial unit to the next. The concept of β-diversity or turnover can include changes in diversity over space and time. Examining species compositional change along any ecological gradient has become an important aspect of monitoring biological diversity (Magurran, 2004), with important applications such as designing and managing protected areas (Wiersma and Urban, 2005; Krishnaswamy et al., 2009). The species compositional change reflects both historical and environmental events (Philippi et al., 1998). Recent studies have conceptualized and refined the idea of species turnover (Whittaker, 1960; Wilson, 1984; Borcard et al., 1992; Lande, 1996; Gering et al., 2003; Koleff, 2003) with clear illustrations of methodology (Jost, 2007; McDonald and Hillebrand, 2007; Baselga, 2010; 2012, 2013; Soininen, 2010; Tuomisto, 2010, Veech, 2010; Anderson et al., 2011; Robert and Meelis, 2014). Despite this, there exists an ambiguity regarding the drivers of the species turnover across multiple spatial scales.

River systems are linear net-works that are nested at multiple spatial scales from head-waters to large river channels. Therefore, they offer unique opportunities to test spatial structure in aquatic communities (Al-Shami et al., 2013; Hauer and Lamberti, 2007). Beta-diversity is known to depend on spatial scale since geographic proximity may be correlated with species similarity (Boyero, 2003; 2011; Heino et al., 2015). Fish species diversity is influenced by biotic and abiotic processes that function across various scales of space and time in riverine systems (Pegg, 2007). Some of these processes operate at very coarse temporal and spatial scales. At larger scales, biotic processes such as speciation and dispersal associated with geomorphology and tectonics strongly influence the pattern of fish diversity within and among river systems. However, at finer spatial scales, the flow of water across the fluvial landscape influences fish species diversity, as it can have strong effects on biotic factors such as dispersal and trophic interactions (predation etc) (Pegg, 2007). Abiotic factors related to local geology, and river-channel morphology are largely determined by the interaction between the flow regimes of a river which play a crucial role in determining the types of suitable habitat available for riverine fishes throughout the various stages of their life history (Bunn and Arthington, 2002; Pegg, 2007).

River valley projects are known to transform natural landscapes and the riverscapes within them which probably affect river and associated freshwater ecosystems in many ways (Dudgeon, 2000 a, b; Vorosmarty et al., 2010). Their impacts are often reflected in changing the spatial patterns of fish assemblages (Dudgeon, 2011). Particularly, dam construction can fragment basins, affect fish assemblages directly by eliminating or reducing movement of fishes, which then leads to reduction of upstream/downstream species richness especially that of migratory species (Gillette, 2005). Dams also alter connectivity (Pringle, 2001) and have substantial cumulative effects on fish biodiversity at a regional scale. The effect of dams was shown to last for more than a decade after its construction, which led to changes in the fish guild composition at downstream sections of a river in Brazil (Vasconcelos et al., 2014a). On the other hand, homogenization in river systems due to the impact of invasive species and channel modification (Bertuzzo, 2009) will have an effect on fish species composition.

Studies on species composition and turnover are relatively fewer in Indian river systems. Previous studies on species turnover in Indian river systems have suggested that species compositions across upstream/downstream reaches are more similar to each other than the upstream and downstream reaches in the same river (Bhat, 2003). Understanding of spatial turnover of stream fishes in the WG is of considerable interest to biogeographers and also serves as an evaluation of the adequacy of the PA network in the protection of fish diversity. Further, it can enhance our understanding of how fish species composition is affected in altered river systems.

In this chapter, I chose two adjacent river sub-basins from the Western Ghats (WG) to answer two questions: 1) What drives the fish species turnover between river segments within a sub-basins? 2) How does fish species turnover vary across adjacent river basins? I hypothesize that the similarity in environmental variables will determine fish species composition in addition to geographic distance (Leprieur et al., 2009).

Materials and Methods

Study Site

The study was conducted in the WG Biodiversity Hotspot and a UNESCO World Heritage site in India (Das et al., 2006; Kasturirangan, 2013). I chose Bhadra and Tunga rivers that are separated by a hill range situated at 1160 m near Gangamoola in the Kudremukh National Park and have similar topographic and climatic features. Both these rivers are tributaries of Krishna river: a major east-flowing river in peninsular India (Fig. 3.1). Bhadra and Tunga catchments are dominated by tropical wet evergreen forest and montane habitats which comprise stunted evergreen forests (sholas) in a grassland matrix. These sub-basins are fed by numerous perennial streams and exhibits a wide array of stream habitat types such as runs, pools, cascades and riffles.

Sampling strategy

In Bhadra, I sampled stream segments across an elevation range from 600 m to 1160 m. The sampled segments covered a range of riverine habitats that are essential for fish fauna. In Tunga, the elevation range covered was between 600 m and 900 m. The major habitats sampled were pool, run, and riffle. I defined a river segment as my sampling unit, which was a stretch of 100-150 m length.

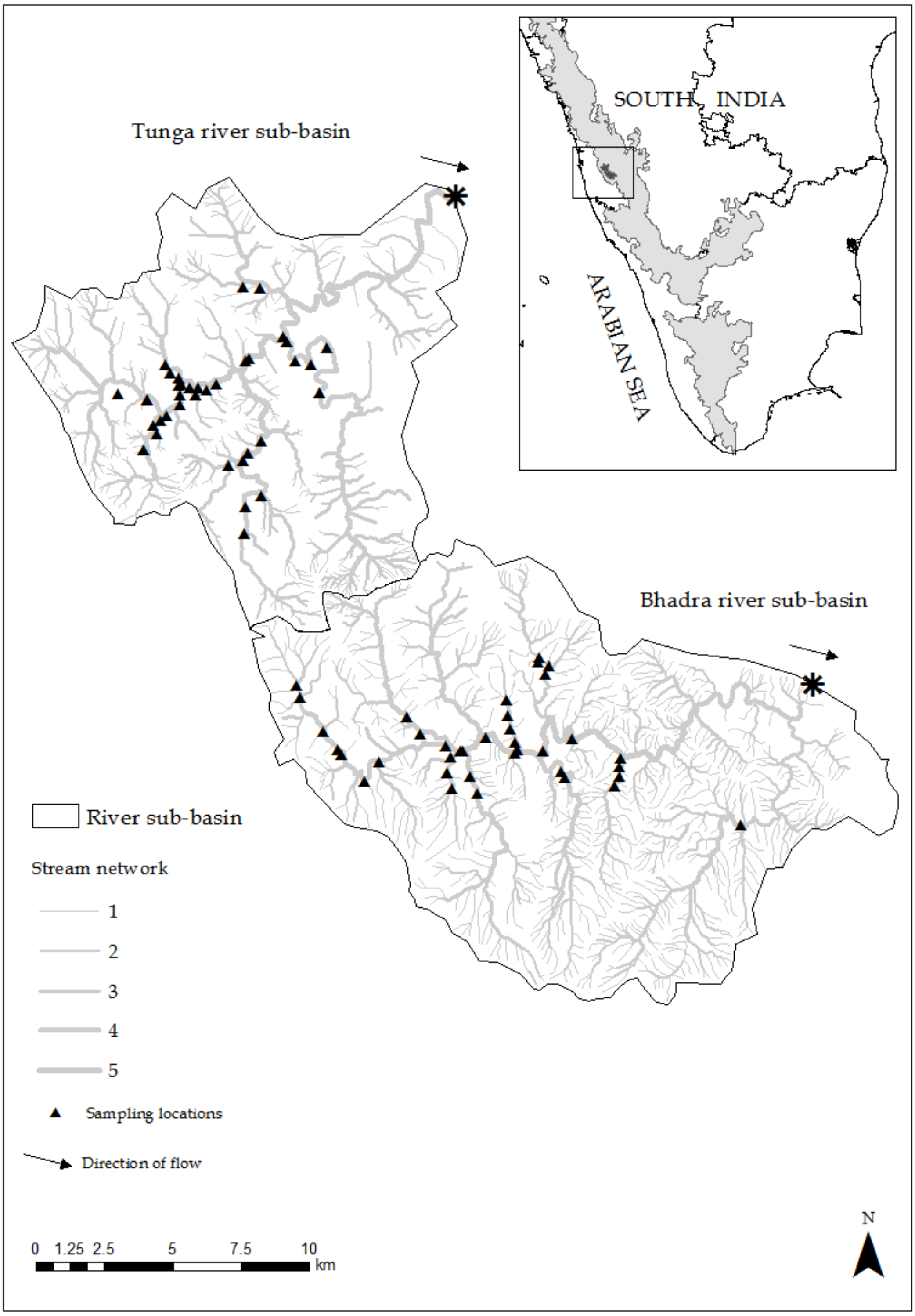

Figure 3. 1. Sampling locations in Tunga and Bhadra river sub-basins.

These segments were nested under different stream orders and spaced approximately 300-500 m distance apart. I used only wet season (June and November-December, 2013) across two sub-basins for this analysis considering the logistical constraints.

Fish sampling

Fish sampling was conducted with the help of castnets (0.5 cm x 0.5 cm and 1.1 cm x 1.1 cm mesh size) as well as with modified fish census method (Arunachalam, 2000; Deacon et al., 2015) at certain river sections where cast netting was not feasible. Each river segment was sampled thoroughly for about 120 minutes, depending on feasibility. Fishes were identified to the species level in the field and were released live at the captured locations after measuring body length in cm. River habitat characteristics data was collected following fish sampling in each sampling segment. This included river width (m), river depth (m), water temperature (^{0}C), electrical conductivity (µS/cm) (model HI98302), total dissolved solids (ppt) (model HI98304), pH (model HI96107), canopy cover (%), and substratum (%). Portable water tracers were used to record electrical conductivity (µS/cm), total dissolved solids (ppt) and pH (Hanna Instruments). River bed substratum was visually categorized into rocks, boulders, sands, gravels and mud, leaves and woods (%). Canopy cover (%) was also noted down at each segment. Segments were re-sampled over two wet seasons from the reverse direction to prevent sampling sequence artefacts. Water samples were also collected from the midsection of each segment for laboratory estimation of other water quality parameters such as total hardness (mg/l), calcium hardness (mg/l), free CO_2 (mg/l), chlorides (mg/l), total alkalinity (mg/l), inorganic nitrates (mg/l) and inorganic phosphates (mg/l). Analysis of water quality parameters was carried out following the standard (APHA; Trivedi and Goel, 1986).

Statistical Analysis

All analyses were performed in R statistical software (R Development Core Team, 2012) using the 'ecodist' package (Goslee and Urban, 2007).

Species composition and turnover

I calculated dissimilarity in species composition (i.e. species turnover) across segments using Bray-Curtis index (that uses relative abundance data). For stream characteristics (variables), I used Euclidean distance between sites to analyze variability in freshwater fish species and environmental covariates (Jackson et al., 2001a). Association between geographical proximity and fish faunal composition was calculated by using Mantel's test. As one would expect, the greater the geographic distance between regions, the less is biological similarity (Goslee and Urban, 2007). A monotonic decrease in Mantel's correlogram would indicate effect of space and the periodic pattern would indicate the influence of habitat configuration rather than pure spatial proximity. I also calculated partial Mantel correlation for all the measured variables to check the influence of variables on dissimilarity in species composition.

Reference composition

I estimated pair-wise dissimilarity between segments and also estimated dissimilarity with respect to a hypothetical reference composition to enable analyses that required a continuous measures of compositional turnover across spatial units. I calculated a hypothetically diverse reference composition by combining all the species encountered in two river sub-basin. I used incidence data both for total as well as for endemic species. I then took sum of all the species for all sampled segment across two basins. Therefore every segment in a study region is related to the reference composition. Dissimilarity was calculated between each segment and the newly created reference composition. Since all the segments were sampled from upstream to downstream directions spaced at 300-500 m distance, paired difference for every segment was calculated by taking an average between immediate upstream and downstream segments of every segment.

Spatial analysis

The dissimilarity was mapped using Arc Map GIS software across different segments. Mapping helped in visually interpreting the degree of spatial dependence present in all the sampled segments. Association between geographical proximity and fish faunal composition was calculated using Mantel's tests and correlogram.

Habitat variables

I also tested for spatial autocorrelation using Mantel's correlograms in stream ecological variables using Euclidean distance between sites for fish species and ecological covariates. To identify if any specific covariates varied in space and predicted species turnover, I used Mantel correlations between similarity and habitat covariates.

Results

Pattern of species composition

In total, I recorded 40 species in Bhadra and Tunga river basins with 5004 individuals. I recorded a total of 20 species with 1829 individuals (36.55%) in Bhadra and 39 species with 3175 individuals (63.44%) in Tunga (Appendix – 3.1). The Mantel's correlogram indicated a sine-hole pattern, which represented high turnover at small spatial distance (up to 5 km) across Bhadra Tunga sub-basin (Fig.3. 2). Species turnover or dissimilarity in species composition was strongly correlated with the geographic distance (Mantel's r = 0.16, p = 0.0001). Similarly, I calculated Mantel's correlogram for individual river basin. In Bhadra, species turnover effect was weakly correlated or uncorrelated with geographic distance (r = -0.013, p = 0.97), it becomes positive after 5 km (Fig. 3. 3).

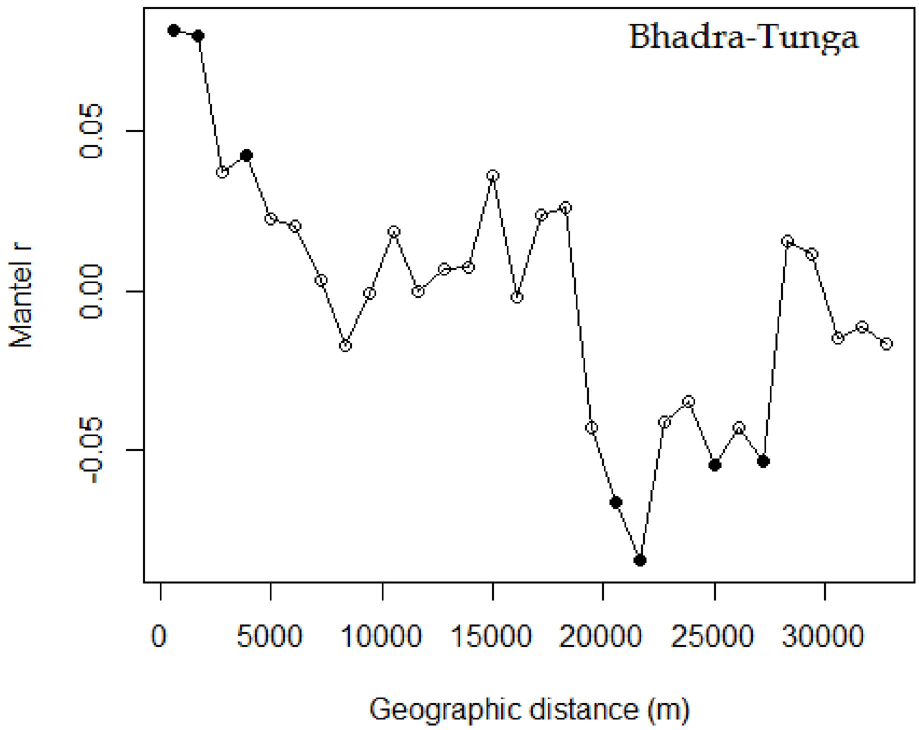

Figure 3.2. Relationship between species dissimilarity as a function of geographical distance for Bhadra Tunga combined. Correlogram shows a sine-hole pattern where sites which are closer are also geographically similar (indicated by filled circles) than sites that are farther apart. Species turnover is high up to a distance of 15 km and strongly correlated with geographical distance (Mantel's r = 0.16, p=0.0001) and the effect of species turnover becomes positive after a distance of 10 km.

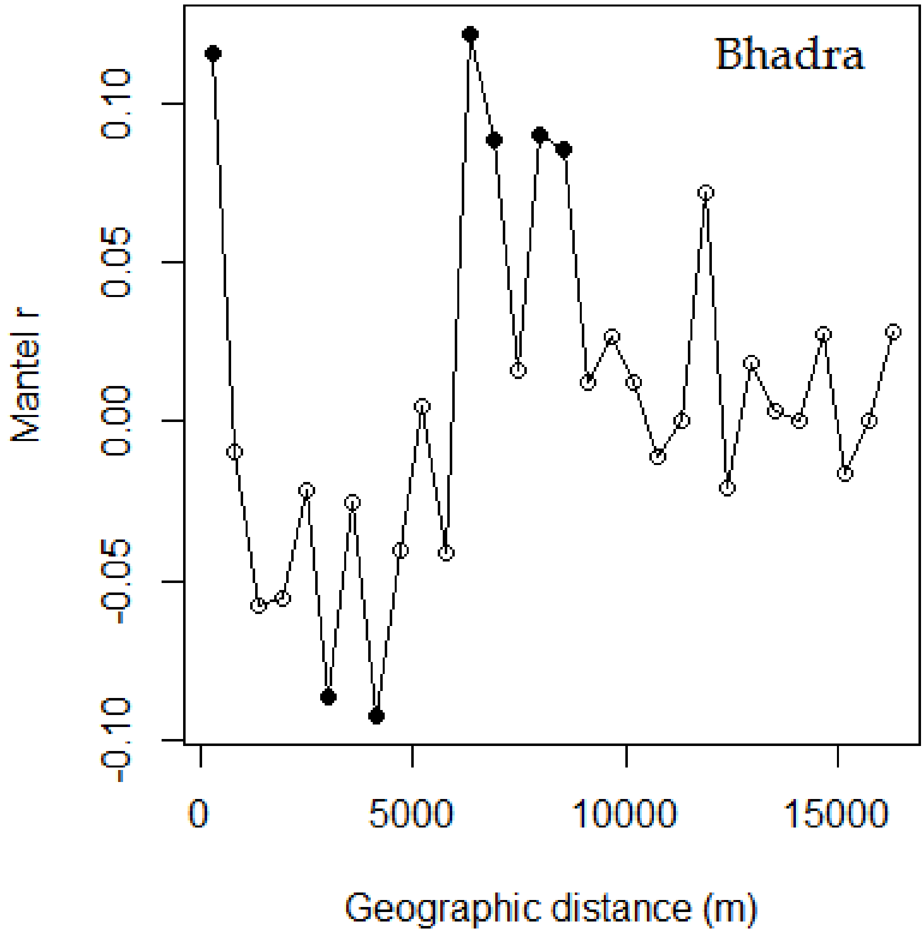

Figure 3.3. Correlogram showing the relationship between pairwise dissimilarity and geographical distance in Bhadra. Species turnover effect is weakly correlated with geographic distance (r =-0.013, p = 0.97) and it becomes positive after 5 km distance in Bhadra.

In the case of Tunga, species turnover was high at smaller spatial scales (up to a distance of 1-2 km). Species turnover was strongly associated with geographical distance (Mantel r = -0.21, p = 0.002), Fig. 3. 4).

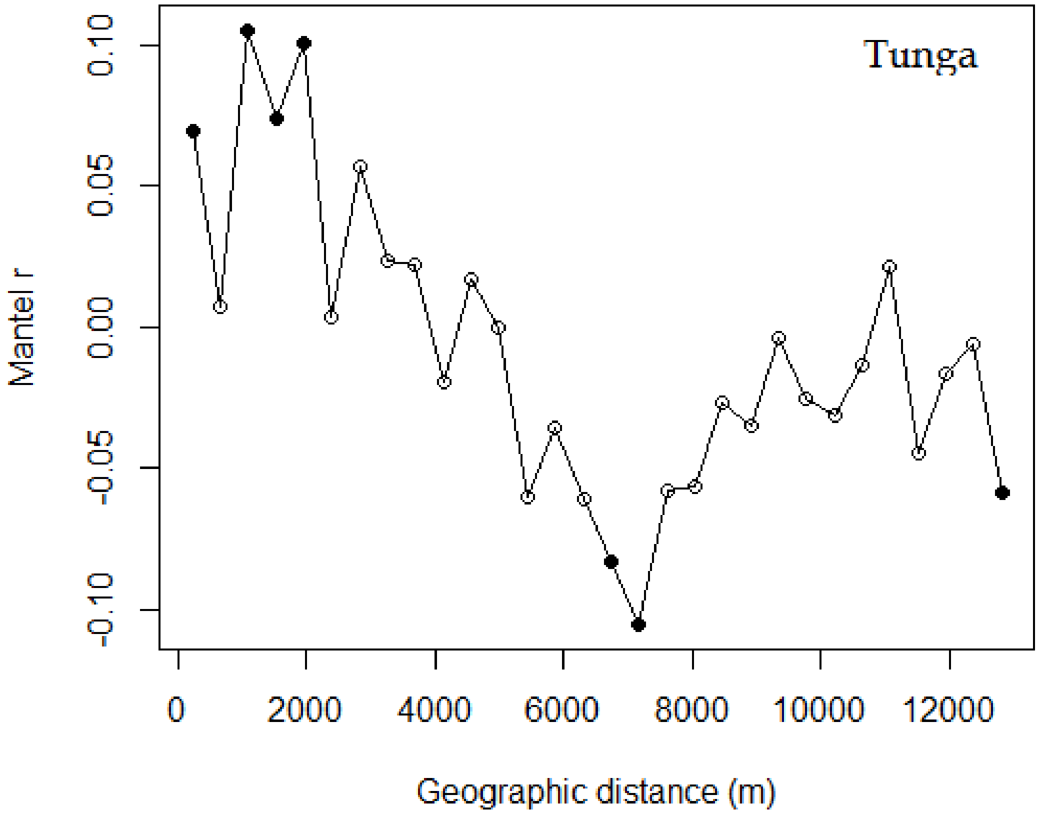

Figure 3. 4. Correlogram showing the relationship between pairwise dissimilarity and geographical distance in Tunga. Compositional dissimilarity (species turnover) showed a sine-hole pattern with high species turnover at smaller spatial scales (up to a distance of 1-2 km). In other words, compositional dissimilarity was strongly associated with geographical distance (Mantel r=-0.21, p =0.002).

Drivers of species composition

Species turnover in Bhadra (up to 5 km) (Fig. 3. 3) and (up to 6 km) in Tunga (Fig. 3. 4) indicated the greater habitat connectivity and fish mobility. The high turnover was attributed to local factors (variation in habitat quality and biophysical parameters) rather than effects of spatial proximity. Mantel r was significant and positively correlated with geographical distance (0.16), rocks (0.19), boulders (0.11), pebbles (0.13) and water temperature (0.11) and negatively correlated with electrical conductivity in combined Bhadra-Tunga sub-basins (Table 3. 1).

Table 3. 1. Mantel's test shows the relationship between pairwise dissimilarity in species composition and dissimilarity in ecological covariates for Bhadra Tunga sub-basin (combined).

Covariates	Mantel r (p value)	2.5% llim	97.5% ulim
Geographical distance***	**0.16** (0.0001)	0.14	0.19
Rocks**	**0.19** (0.004)	0.14	0.22
Boulders**	**0.11** (0.006)	0.07	0.15
Pebbles**	**0.13** (0.003)	0.10	0.17
Stream order	0.09 (0.02)	0.05	0.12
Slope	0.06 (0.07)	0.037	0.100
Depth width ratio	0.081 (0.87)	0.04	0.14
Water temperature*	**0.11** (0.03)	0.08	0.14
Electrical conductivity	-0.06 (0.87)	-0.11	-0.03
pH	0.08 (0.11)	0.04	0.10
Partial Mantel r	0.04 (0.14)	0.01	0.08

*Statistical significance alpha = 0.05: (p-values * p <0.05, ** p <0.01, *** p <0.001)

In Bhadra, Mantel's r was significant and positively correlated with stream order (0.15), rocks (0.15), and canopy cover (0.14) while it was negatively correlated with depth- width, and EC indicating that the overall richness was low (20 species) but with different species composition (see Table 2 for more detailed species list). The distinct composition was mainly due to the endemic and habitat specialist fish such as, *Garra stenorhynchus.* Similarly, in Tunga, the Mantel r was significant and positively correlated with gravels rocks (0.31), boulders (0.21), stream order (0.20), and depth-width ratio (0.22), water temperature (0.17) and pH (0.16) etc (see Table 3. 3 for detail).

Table 3. 2. Mantel's test shows the relationship between pairwise dissimilarity in species composition and dissimilarity in ecological covariates in Bhadra sub-basin. Species turnover was driven mainly by stream characteristics (stream order, canopy cover) and local habitat effects (rocks).

Covariates	Mantel r (p value)	2.5% llim	97.5% ulim
Geographical distance	-0.13 (0.97)	-0.17	-0.09
Stream order**	**0.15** (0.03)	0.08	0.22
Canopy cover**	**0.14** (0.08)	0.10	0.18
Rocks**	**0.15** (0.08)	0.10	0.20
Slope	0.09 (0.11)	0.02	0.16
Depth width ratio	-0.021 (0.55)	-0.07	0.07
Electrical conductivity	-0.02 (0.58)	-0.10	0.05

Covariates	Mantel r (p value)	2.5% llim	97.5% ulim
pH	0.09 (0.18)	0.14	0.13
Partial Mantel r	0.09 (0.12)	0.03	0.16

Statistical significance, alpha = 0.05: (p-values * p <0.05, ** p <0.01, *** p <0.001)

Table 3. 3. Mantel's test shows the relationship between pairwise dissimilarity in species composition and dissimilarity in ecological covariates in Tunga sub-basin. Species turnover was mainly influenced by geographical distance, stream characteristics (depth-width ratio, stream order), local habitat (rocks, boulders) and water chemistry (electrical conductivity and pH).

Covariates	Mantel r (p value)	2.5% llim	97.5% ulim
Geographical distance**	**0.21** (0.002)	0.16	0.28
Rocks**	**0.31** (0.002)	0.23	0.37
Boulders**	**0.21** (0.007)	0.14	0.27
Stream order**	**0.20** (0.006)	0.13	0.25
Slope	0.01 (0.36)	-0.04	0.06
Depth width ratio**	**0.22** (0.008)	0.08	0.27
Water temperature**	**0.17** (0.009)	0.13	0.23
Electrical conductivity	-0.09 (0.86)	-0.14	-0.02
pH**	**0.16** (0.05)	0.08	0.21
Partial Mantel r	0.19 (0.007)	0.12	0.25

Statistical significance, alpha = 0.05: (p-values * p <0.05, ** p <0.01, *** p <0.001)

The overall richness (40 species) was very high and the species composition was very different, as more than 20 unique species (*Paracnthocobitis mooreh* and *Balitora mysorensis* etc) were found in Tunga sub-basin alone, suggesting importance of stream heterogeneity (See Appendix – 3.1 for complete species list). Dissimilarity in species composition across segments with respect to a hypothetical combined pooled reference composition was higher in Bhadra than Tunga, while in case of endemic species composition was higher in Tunga than Bhadra (Appendix 3. 2 a & b). Incidence based data showed higher dissimilarity in species composition and endemic species composition in Tunga compared to Bhadra (Appendix 3. 3 a and b).

Discussion

This study offers interesting insights into fish species composition (species turnover) at smaller spatial scales in two river sub-basins of the WGs, India. Geographic proximity (dispersal limitation) did not result in higher species turnover, suggesting beta diversity patterns might be controlled by niche related processes (habitat complexity and biophysical factors). Among environmental factors, stream order, rocks and canopy were highly correlated with fish species composition in Bhadra sub-basin, while in Tunga sub-basin, stream substratum (gravel, rocks and boulders) determined fish species composition (Table 1). Dissimilarity in species composition across segments was higher in both the river sub-basins implying partial species turnover across sampled segments for both total and endemic species (Appendix 3.2 a & b). Dissimilarity in species composition across segments was consistently higher in Tunga (based on incidence data) than in Bhadra (Appendix 3.3 a & b) indicating higher species turnover in Tunga than in Bhadra. Stream fishes are comprised of good as well as poor dispersers. Rheophilic (with greater swimming ability) species are mostly surface dwellers (*Barilius* sp, *Salmophasia* sp, *Tor* sp) and seem to be highly mobile both in the main river channel as well as among all the tributaries draining the main channel (Atkore et al., 2017). However, there are headwater and habitat specialist fishes that restrict themselves to specific habitats (*Balitora* sp, *Pethia* sp, *Glyptothorax* sp) and therefore can be categorized as poor dispersers (Atkore et al., 2017). Water chemistry especially water temperature and dissolved oxygen (in riffle dominated habitats at headwater and mid sections of streams) seems to govern mobility of headwater fish species.

Overall, the Bhadra sub-basin was impoverished with only 20 species. The high topography and presence of a water fall could have hindered fish migration from lower elevations to the higher elevations. Many fishes were headwater specialists. On the other hand, Tunga river-sub-basin had a gentle elevational gradient with diverse stream habitats with few natural river barriers (waterfalls). Fish movement could have been easier within the main river channel as well as across different tributaries. This results in the higher observed species richness and unique species composition. Bhadra sub-basin could be treated as subset of Tunga species composition since, all the species of Bhadra (except one species i.e. *Garra stenorhynchus*) were also found in Tunga. Additionally, Tunga had 20 unique fish species in its habitat making it the most species rich sub-basin sampled in the study. About 19 species were common in two sub-basins (Appendix – 3.1). Thus, headwater habitat that is richer in cool temperatures, dissolved oxygen, substrate composition and canopy cover seems to be vital for habitat specialist and endemic fish species. Preserving such crucial habitats is critical for sustaining endemic fish populations.

This study suffers from a few caveats. I could only use wet season data to estimate fish species turnover as adequate coverage of sampling sites was available only for this season. It is known that seasonal variation influences fish diversity and species turnover (Adams et al., 2004; Shimadzu et al., 2013; 2015). Covering multiple seasons across sampling sites would be important in future studies. The spatial coverage of this study was small, and I was able to just cover approximately 500 m elevation gradient within the Kudremukh National Park consisting mostly a headwater region. Future studies in this region should cover the lower parts of the elevational gradient as well.

This study offers insight into stream habitat variables that influence distribution of fish assemblages within a basin at high to middle elevation zones. The knowledge from this study offers insights for prioritizing stream segments with specific stream habitat characteristics for fish conservation within these basins.

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Chapter 4
River barriers and environmental variables influence fish guild responses in the Western Ghats of India

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River barriers and environmental variables influence fish guild responses in the Western Ghats of India

Introduction

Freshwater is vital to sustain biodiversity as well as human well-being (Baron, 2003; Dudgeon et al., 2006; Vorosmarty et al., 2010), but freshwater ecosystems are among the most affected by anthropogenic impacts in the world (Dudgeon, 2010; Strayer, 2010; Vorosmarty et al., 2010) and a high proportion of riverine biodiversity is endangered (Darwall et al., 2008; Dudgeon, 2000; Moreno and Rodriguez, 2010; Nel et al., 2007). As tropical rivers have been altered by various anthropogenic interventions including dams, barrages, and other river regulation schemes to meet water and energy needs, the impacts of flow regulation and water abstraction on freshwater biodiversity and ecosystem services have been generally neglected (Bunn and Arthington, 2002; Moreno and Rodriguez, 2010; Poff and Zimmerman, 2010). As a result, the highly diverse taxon of freshwater fishes (>5000 species worldwide) is listed as the most threatened vertebrate group by the International Union for Conservation of Nature (Reid et al., 2013).

Man-made barriers disrupt the longitudinal and lateral connectivity of river systems (Pringle, 2001; Vannote et al., 1980), often with highly negative effects on fish communities (Konar et al., 2013; Malmqvist and Rundle, 2002; Poff and Allan, 1995). Dams have both immediate as well as long-term effects on life histories of fishes (Vasconcelos et al., 2014a, b). Though dams and reservoirs might benefit some generalist (and invasive) fish species (Chu et al., 2015), overall they negatively affect the diversity, abundance, life-history traits, and breeding success of many specialist and endemic fish species (Dudgeon, 2000; Pringle, 2001; Mims and Olden, 2012; 2013; Reid et al., 2013). For instance, dewatering by a small dam in Costa Rica in the downstream section affected the life history strategies of fishes such as cichlids, with complex reproductive requirements (Anderson et al., 2006). A study in the Colorado River found that regions with high densities of dams benefited invasive and exotic species with equilibrium life history strategies over native fish species with opportunistic / periodic breeding and growth patterns (Pool et al., 2010). Similarly, hydropeaking operations downstream of the Itutinga dam led to the disappearance of insectivorous fish communities in the Grande river basin in Brazil (Gandini et al., 2014). Apart from hydrological and environmental variables, natural factors such as basin geomorphology, biotic interactions, land use history, as well as anthropogenic disturbances such as water abstraction, also influence fish communities (Gilliam et al., 1993; Jackson et al., 2001b). Local human-induced disturbances from illegal fishing, pollution, and substrate mining pose further threats to fish feeding and breeding habitats (Daniels, 2002). Such disturbances can either exert these effects independently, or flow barriers can aggravate their effects. As a result, it often becomes difficult to separate local anthropogenic effects from larger basin-scale effects due to modifications of water quantity and quality. Knowledge is still fairly limited about the impacts of multi-scale threats on freshwater fish diversity in tropical Asian river systems (Bhat, 2002).

Available studies on freshwater fish diversity describe the functional responses of fish guilds to riverine habitat gradients or stream characteristics, but do not adequately quantify the effects of environmental covariates and local disturbances in relation to flow regulation (De Silva et al., 1979; Bhat, 2004; Weliange and Amarsinghe, 2007; Johnson and Arunachalam, 2012; Chakravarty and Homechaudhuri, 2013). But, few recent studies have quantified and modelled the functional guilds of fishes in relation to flow regime and habitat characteristics (Oliveira et al., 2012; Macnaughton et al., 2016). In India, despite a high diversity of freshwater fish fauna, studies on factors driving persistence of various fish guilds in hydrologically altered and human-modified river systems are relatively few (Jayaram, 2010; Raghavan et al., 2016). Guild-based approaches can provide an intuitive understanding of the functional responses of fish communities to alterations (Villager, 2008) and could help in developing a broad understanding of the impact of river modification on fishes (Mouillot et al., 2013). Earlier studies from the global biodiversity hotspot of the Western Ghats (WG) in India showed that fish communities partitioned habitat space based on their eco-morphology and in relation to stream substrate (Bhat, 2005), higher species richness occurred at lower elevations (Raghavan et al., 2008), and that regulated rivers differed strongly from non-regulated rivers in fish assemblage structure (Bhat and Magurran, 2007). Despite a growing body of work on fish taxonomy and community ecology in India, relatively few studies have explicitly compared guild-wise species richness in regulated and non-regulated river basins

(Kundu et al., 2014).

I adopted a guild-based approach to assess ecological responses of fish species richness of three guilds (based on position in water column) to river barriers, water chemistry, and local water abstraction in the central Western Ghats (WG's) of India. I defined river barriers as "anthropogenic modifications of flows by dams or barrages to alter the river's flow regime". River barriers are mainly major and minor barrier. Minor barriers consist of small check dams with height of < 1.2 m, width < 50 m and an impoundment area of < 10 sq.km while major barriers include check dams with highest > 1.5 – 2 m, width > 50 -150m and an impoundment area > 11 sq.km (Atkore et al., 2017). Based on comparisons of regulated and non-regulated sub-basins (called RSB and NRSB), the study addressed three questions: 1) how do fish guild richness and species composition vary across regulated and non-regulated sub-basins? 2) how do environmental covariates and local anthropogenic disturbance (water abstraction) differ between RSB and NRSB? and 3) how do environmental covariates vary with guild-wise fish species richness in RSB and NRSB? Based on predictions of previous studies (Brasher, 2003; Merz, 2013; Macnaughton et al., 2016), I hypothesized that river segments in regulated sub-basins will have higher temperature and poorer water quality than river segments in non-regulated basins. I discuss the results in light of the potential impacts of river barriers and local disturbance on three water column position-based guilds. I also discuss the choice of this guild-based classification for studies on freshwater fishes in human modified tropical river systems. Finally, I outline the implications of our findings for mitigating effects of flow regulation, monitoring river habitats, and developing guidelines for ecological flow regimes in the region.

Materials and Methods

Study Site

The study was conducted in the states of Karnataka and Goa in the central WG's region of India from 2011-2014 (Figure 1). The WG mountain range along the western coast of India is a distinct zoogeographical subdivision of Peninsular India (Bhimachar, 1945) and a global biodiversity hotspot and a world heritage site (Cincotta et al., 2000; Das et al., 2006), with some of the highest human population densities in the world. I conducted sampling across two regulated sub-basins (RSB, Malaprabha and Mhadei), and two non-regulated sub-basins (NRSB, Bhadra and Tunga). The Malaprabha and Mhadei (aka Mahadayi/Mandovi) originate from the same hill range at 760 m elevation bordering the states of Goa and Karnataka. The headwater catchments of Malaprabha and Mhadei are dominated by tropical moist evergreen forest and the downstream plains are mostly covered by agriculture and some scrub forest. These sub-basins receive heavy southwest monsoon rainfall from June to September. In Malaprabha, the annual rainfall varies from 2000 to 3500 mm and average annual stream discharge is 1944 million cubic metres (MCM) yr^{-1}. Average annual rainfall recorded for the Mhadei sub-basin was 3955 mm and average annual stream discharge was 3447 MCM yr^{-1} (Ibrahampurkar, 2012). There are numerous barrages and check-dams built on both rivers to store dry season flows from the headwater catchments for irrigation (Ibrahampurkar, 2012). An inter-basin water transfer project is underway on two headwater tributaries of Mhadei sub-basins to divert 7.56 TMC (thousand million cubic feet) water annually to provide drinking water for some towns and villages in Karnataka State. In the last two decades, the cropping pattern in the Malaprabha catchment has changed from rainfed crops such as millets and pulses to water-intensive crops such as sugarcane, vegetables, and oilseeds. As a result, water extraction from the river and groundwater has intensified (Heller et al., 2012), drastically affecting stream flows during both the monsoon and dry season. Municipal wastewater and fertilizer runoffs from agricultural fields have seriously lowered river fish productivity, according to local communities in the area. Other local disturbances to stream biota in the area are from fishing and sand-boulder mining.

The non-regulated sub-basins of Tunga and Bhadra are spread across the Chikkamgaluru, Dakshina Kannada, and Udupi districts of Karnataka. The headwater streams originate at approx. 1160 m elevation in the Kudremukh National Park (KNP). The region receives more than 6000 mm of rainfall annually (Krishnaswamy et al., 2006). These sub-basins have evergreen forests in the headwaters, while downstream reaches have interspersed paddy fields and coffee plantations (Appendix 4.1 -S1A Table).

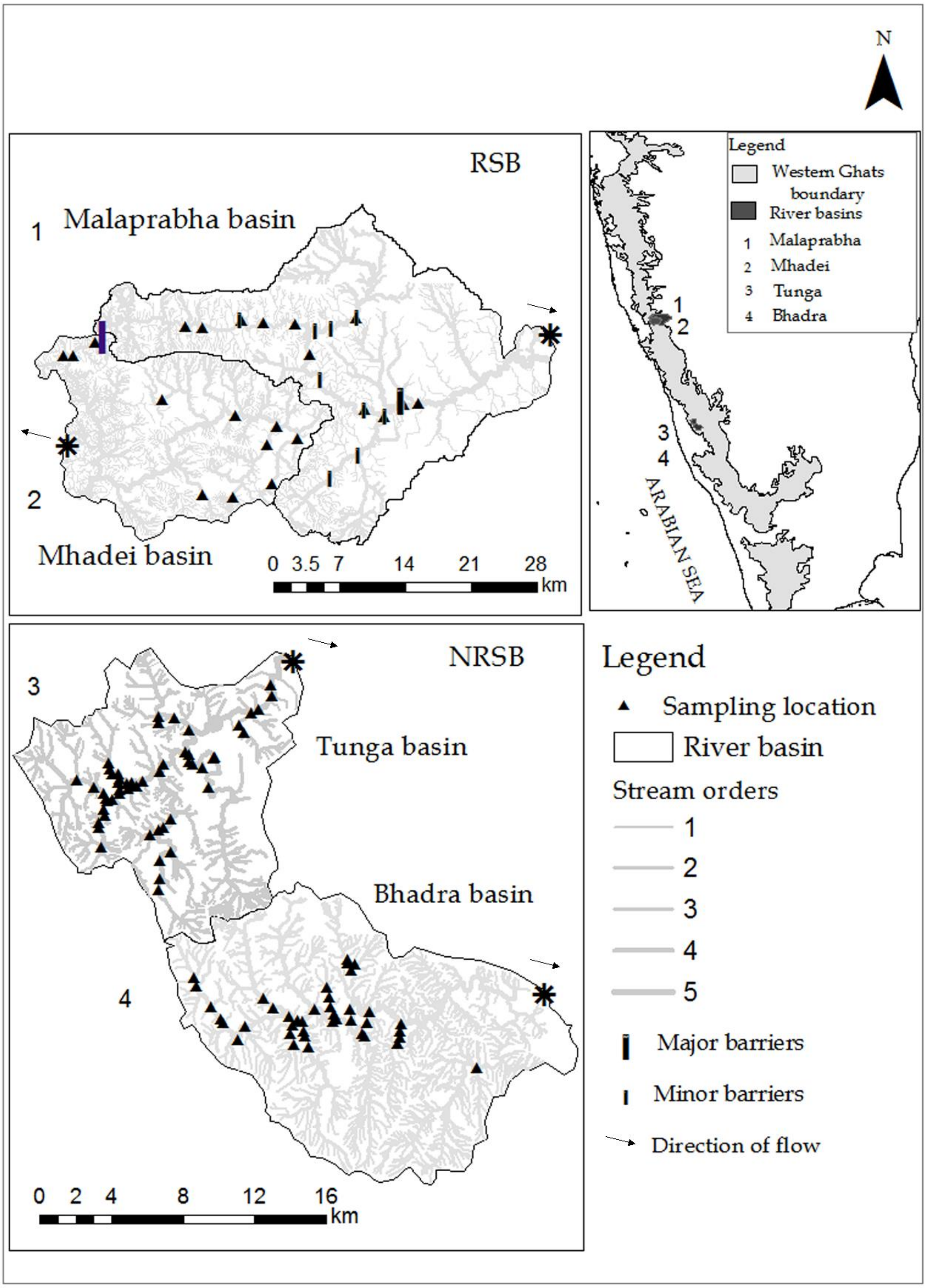

Figure 4. 1. Sampling locations in the four sub-basins in the central Western Ghats, India (1 = Malaprabha 2 = Mhadei 3 = Tunga 4 = Bhadra).

Hydrological time-series for regulated river sub-basins (RSB)

Data on river discharge (cumecs) were obtained for Malaprabha and Mhadei for the period from 1979 to 2013 from the Water Resource Development Organization (WRDO), Karnataka and the Department of Water Resources, Goa. Streamflow data from gauging stations located at Collem and Ganjem (for Mhadei river), and Khanapur (for Malaprabha river) were used. Similar datasets could not be obtained for the non-regulated Bhadra and Tunga sub-basins due to absence of stream gauging stations in this part of the study area. Daily rainfall time series data (in mm) were extracted from gridded APHRODITE datasets (spatial resolution of 0.25 x 0.25 degrees (Yatagai et al., 2012) to estimate basin-averaged annual rainfall from 1979 to 2013.

Fish sampling

Fish communities were sampled and corresponding ecological variables were collected from the segments of approximately 150 m length across the 4 sub-basins. The chosen river segments located in both regulated and non-regulated sub-basins had similar elevation ranges (600 m to 930 m), land-use, stream order (2-6) and habitat characteristics (pool, run, riffles) to control for the effects of these variables on species turnover to the extent possible. At each of these river segments, fish sampling was conducted with cast-nets of 0.5 cm x 0.5 cm and 1.1 cm x 1.1 cm mesh-sizes. I relied on using cast nets over other fishing methods because they are known to provide the best coverage and capture of different fish guilds (irrespective of position in the water column) in rivers of the WG's. Further, castnets are a non-destructive fishing technique with the lowest fish mortality (Abraham and Kelkar, 2012; Ahmad et al., 2013) among competing and more intensive methods. Ease of operation, high sampling efficiency and portability enable cast nets to provide better access in sampling locations and habitats in relatively remote river reaches. The overall cast-net effort yielded 79 fish species, which represented nearly 75.23% of the total pool (105 species) known from the study area (Rema Devi et al., 2013), from which we deemed the overall effort as adequate. Sampling was continued until saturation in species accumulation with increasing cast-net effort was observed at each segment (Abraham and Kelkar, 2012). Each replicate thus included the total occurrence data from all casts (10 to 26) conducted over approximately 120 minutes at each river segment. In each segment I conducted cast-netting strategically and based on initial checks on the feasibility of sampling run, riffle, and pool habitats. At some sections of river habitat, visual methods were used (Arunachalam, 2000; Deacon et al., 2015) to complement cast-net effort in recording species occurrence. At each river segment, fishes were caught, identified, measured (total length in cm) and released live into the water. Only 3-5 individuals of unidentified fish species were collected and preserved in 4% formaldehyde solution for further identification in the lab. Standard field guides (Daniels, 2002; Jayaram, 2010) were used for species-level identification and validation (Eschmeyer, 2015). Any evidence of disease or deformity in the fish species sampled was recorded in each segment.

Environmental and water quality variables such as river depth, temperature, dissolved oxygen, calcium hardness, total dissolved solids, canopy cover, river substrates (%) were measured for all segments (Appendix S1B Table). I also recorded the level of disturbance (low, medium, or high) based on observed activities deemed harmful to fish species (water abstraction, fishing, substrate-mining, etc). The intensity of these activities was ranked through direct visual observations.

Guild-based classification of fish species

I grouped all sampled fish species according to six classification schemes (see analysis methods and Table 4. S2), based on intensive field surveys and a review of published (journal articles, field guides) and unpublished (reports, monographs) literature. Fish species were classified based on depth or water column use i.e. surface dwellers, mid-column dwellers and bottom dwellers (Lowe-McConnell, 1975, 1987; Arunachalam, 2000; Bhat, 2002), feeding preferences, (phytophagous, heterotrophic, and omnivorous) (Arunachalam, 2000; Bhat, 2002; Weliange and Amarsinghe, 2007; Johnson and Arunachalam, 2012; Froese and Pauly, 2016;), flow-responses (eurytopic, limnophilic, and rheophilic) (Aarts and Nienhuis, 2003; Chakrabarty and Homechaudhuri et al., 2013), sensitivity to disturbance (Daniels, 2002) reproductive strategies (lithopelagophils, lithophils, pelagophils, phytolithophils, phytophils and psammophils), and life-history cues (equilibrium, opportunistic, periodic/seasonal and intermediate strategist) (Welcomme, 1985; Winemiller et al., 2006; 2008), and endemicity to the WG's region (Daniels, 2002; Dahanukar and Raghavan, 2013).

Data Analysis

Choosing representative guilds for further analyses

Non-metric Multidimensional Scaling (NMDS) is an ordination method that uses dissimilarities calculated from community data collected across sites. This assists in segregating sites with similar assemblages that tend to be closer to each other than sites with more dissimilar assemblages (Borcard et al., 2011). Instead of conventional site-by-species ordination, a trait-by-species ordination with NMDS was used to identify how species clustered together based on the similarity of their classification into different guilds (based on life-history traits related to feeding, reproduction, movement etc.). A presence-absence matrix was prepared for all species (in columns) and all traits (in rows) to run the NMDS analysis until it attained a stable configuration (Borcard et al., 2011). Based on the analysis, I found that guild classification based on position of fishes in the water column (surface-, mid-column-, and bottom-dwelling fishes) was the most stable and representative of other life-history based classifications that were correlated with fish guilds. The richness of each water column position-based guild was defined as the response variable for further analyses. The guild-based analysis also helped overcome any biases resulting from unknown heterogeneity in taxonomic resolution or systematic biogeographic variations in fish species richness across the RSB and NRSB.

Trend analyses of rainfall and discharge data

Time-series analyses were performed to estimate trends in discharge (cumecs, minimum and maximum, yr^{-1}) and annual rainfall (mm, yr^{-1}) for stations in regulated sub-basins. Sen's slopes were calculated and univariate Mann-Kendall significance tests performed to assess monotonicity of trends in the average, maximum, and minimum values of annual discharge from 1979 to 2013 (Yue et al., 2002) using the R packages 'trend' and 'EcoHydroLogy' (Fuka et al., 2014; Pohlert, 2016).

Variation in fish species composition across RSB and NRSB

Non-metrical multidimensional scaling was used to check whether species composition differed across the four sub-basins. NMDS ordination was unconstrained by environmental variables and driven only by species composition (Rowe, 2007). Environmental variables were subsequently fitted on the NMDS ordination axes to examine which ones correlated with dissimilarities in fish community composition, using the Bray-Curtis measure of dissimilarity (Borcard et al., 2011). These analyses were conducted using the 'vegan' package in the R 3.2.1 software (R core Team, 2013).

Effects of environmental variables on guild-wise fish species richness in RSB and NRSB

To test my hypothesis on the effects of flow regulation and anthropogenic disturbance (water extraction) on environmental variables, I visually compared and statistically tested for significance of differences between the values of environmental variables and water quality across 1) regulated and non-regulated basins, and 2) local water abstraction and pollution.

Principal Component Analysis (PCA) was used to identify correlated variables and to select variables for further regression analyses. Generalized linear regression models (GLMs) with Poisson errors were used to explore the influences of environmental and water quality variables on guild-wise fish species richness separately for RSB and NRSB. Data from the sub-basins were not analyzed together to account for potential variation in fish species detectability and any other sampling effects. I also used generalized linear mixed-effects models with 'basin' as the random effect variable, but found that these models provided estimates very similar to GLMs, and with inconsequential random effects. Variables that had common positive or negative effects on fish guilds across the different sub-basins were later identified. The model fit based on McFadden's Pseudo-R^2 and Akaike Information Criterion (AIC) was used to assess and compare GLMs. The models with the highest fit and lowest AIC were chosen as the best models. GLM analyses were performed in the R core Team (2013).

Results

River discharge trends in RSB

Total rainfall (mm yr^{-1}) showed insignificant change in the Malaprabha and Mhadei sub-basins (Figure 4.2, Table 4. 1). However, a strong negative trend was noted in annual discharge (cumecs) for the period 1979 to 2013 across the gauging stations of the Malaprabha and Mhadei sub-basins (Figure 4. 2, Table 4. 1), highlighting the impact of river regulation.

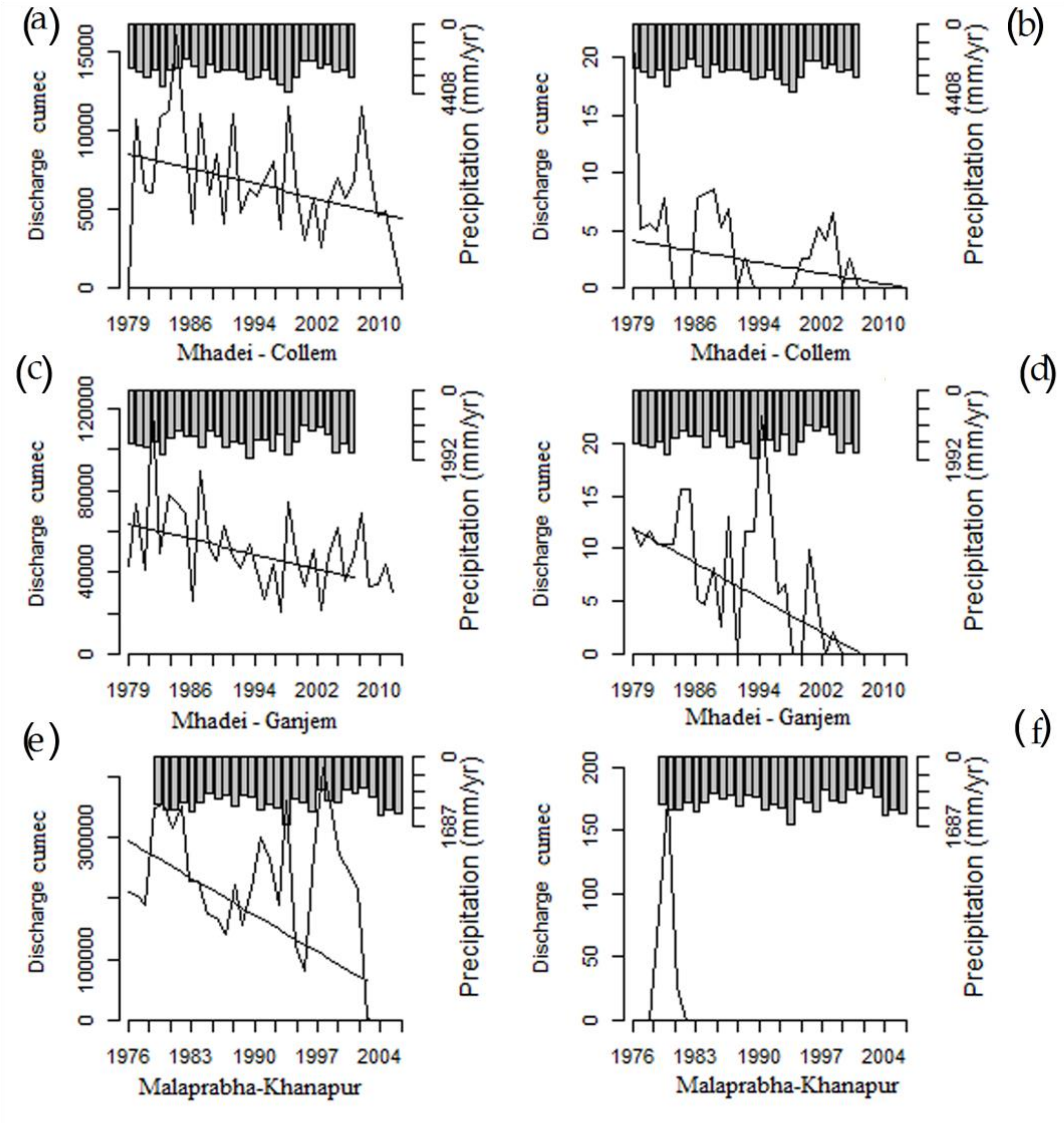

Figure 4. 2. Time-series of maximum (left column) and minimum (right column) values of discharge (cumecs, i.e. m^3/s) and total rainfall (mm/yr) for three hydrological gauging stations in the Mhadei and Malaprabha sub-basin. (a) Mhadei-Collem –maximum discharge (b) Mhadei –Collem- minimum discharge (c) Mhadei-Ganjem –Maximum discharge (d) Mhadei-Ganjem –Minimum discharge (e) Malaprabha – Khanapur –Maximum discharge (f) Malaprabha-Minimum discharge.

Table 4. 1. The Mann-Kendall (M-K) test of significance for total rainfall (mm/yr), and maximum and minimum discharge (m^3/s). A sharp declining monotonic trend in river discharge is noted from 1979 to 2013 despite no significant trends in rainfall time-series, which is likely due to river flow regulation and abstraction of water for irrigation.

Sub-basin	Station	M-K statistic (S)	Kendall's Tau	p-value
Total rainfall (mm/yr)				
Mhadei	Collem	12	0.03	0.83
	Ganjem	-17	-0.04	0.76
Malaprabha	Khanapur	-9	-0.02	0.88
Bhadra	Kudremukh	-21	-0.05	0.70
Tunga	Kerekatte	23	0.05	0.67
Discharge (m^3/s)				
Mhadei	Collem (max)	-147	-0.25	0.04*
	Collem (min)	-192	-0.32	0.003***
	Ganjem (max)	-157	-0.28	0.02*
	Ganjem (min)	-300	-0.504	<0.0001***
Malaprabha	Khanapur (max)	-22	-0.058	0.68
	Khanapur (min)	-58	-0.153	0.03*
Bhadra	Kudremukh	NA	NA	NA
Tunga	Kerekatte	NA	NA	NA

Statistical significance, alpha = 0.05: (p-values * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)

Fish species richness in different habitat guilds

About 12,840 individuals of fish comprising 79 species belonging to 7 orders and 15 families in the 4 sub-basins were sampled from the period 2011 to 2014. Cypriniformes was the most dominant order, with 55 species, (44 endemic species to the WG region) and 67 % of the collected individuals. The most consistent and representative guild classification was found to be based on position of fishes in the water column, by the ordination analysis (Figure 3). Bottom-dwelling fishes (BD) consisted of 5 orders, 9 families and 41 species; mid-column fishes (MCD) had 2 orders, 3 families and 28 species; and surface-dwelling fishes (SD) had 2 orders, 3 families and 10 species (Appendix S2 Table contains details of traits associated with BD, MCD, and SD).

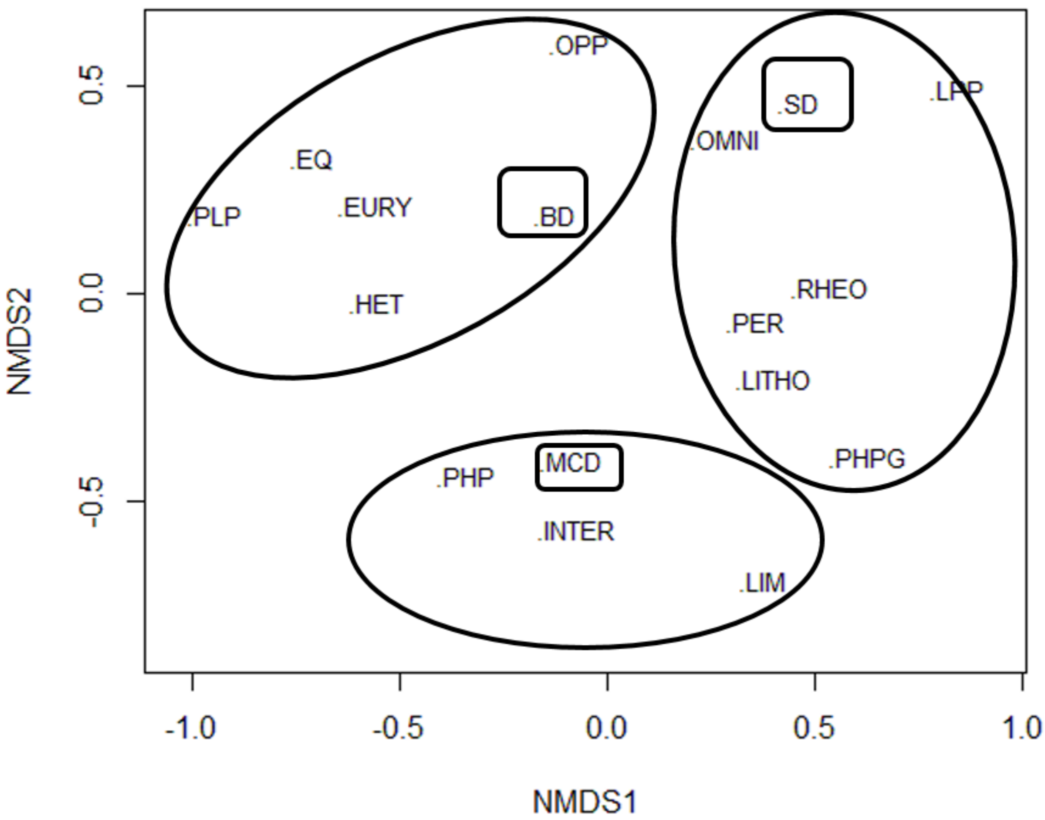

Figure 4. 3. NMDS ordination of the first and second axes shows guild grouping based on fish guild richness. Three clusters shows correlated guild classifications for fish species across the four sub-basins. (Guilds: SD – Surface dwelling, MCD – Mid-column dwelling and BD – Bottom dwelling, EQ – Equilibrium, OPP – Opportunistic, PER – Periodic, IMD – Intermediate, EURY – Eurytopic, LIM-Limnophilic, RHEO- Rheophilic, PLP – Polyphils, LITHO – Lithophils, PHP – Phytophils, PHPG – Phytopelagophils, LPP-Lithopelagophils).

Fish species composition across RSB and NRSB

Species composition was clearly different across RSB and NRSB (Figure 4. 4). The RSBs (Mhadei and Malaprabha) also differed from each other in species composition. Exploratory analyses indicated that most rare and endemic species i.e. 72% (32 out of 44 WG endemic species) were restricted to non-regulated river basins. SD guild richness was higher in NRSB than RSB (*df* = 52.41, t =3.43, p =0.001), whereas species richness was higher for MCD (*df* = 27.38, t =-3.39, p =0.002) and BD (*df* = 27.00, t =-3.98, p =0.0004) in RSB than NRSB (Figure 4.5).

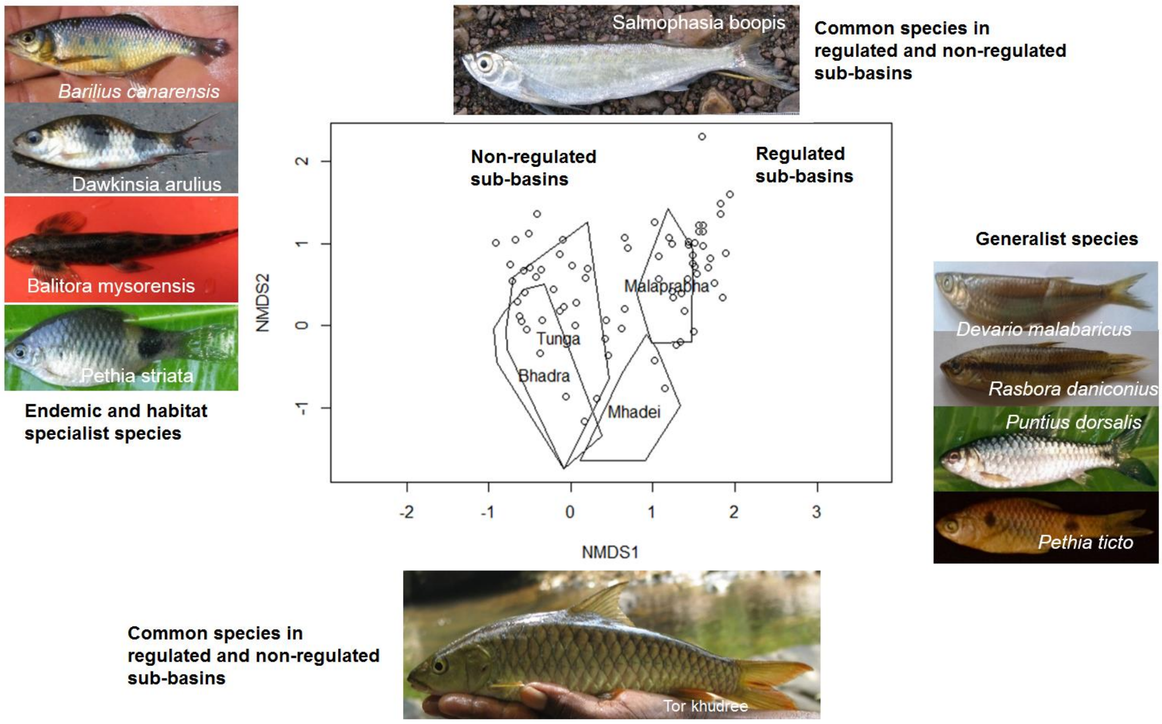

Figure 4. 4. NMDS ordination plot shows fish species composition across the four sub-basins (open circles indicate species). Non-regulated (Bhadra, Tunga) and regulated basins (Malaprabha, Mhadei) differed distinctly in species composition. The Mhadei and Malaprabha also clearly differed from each other in species composition.

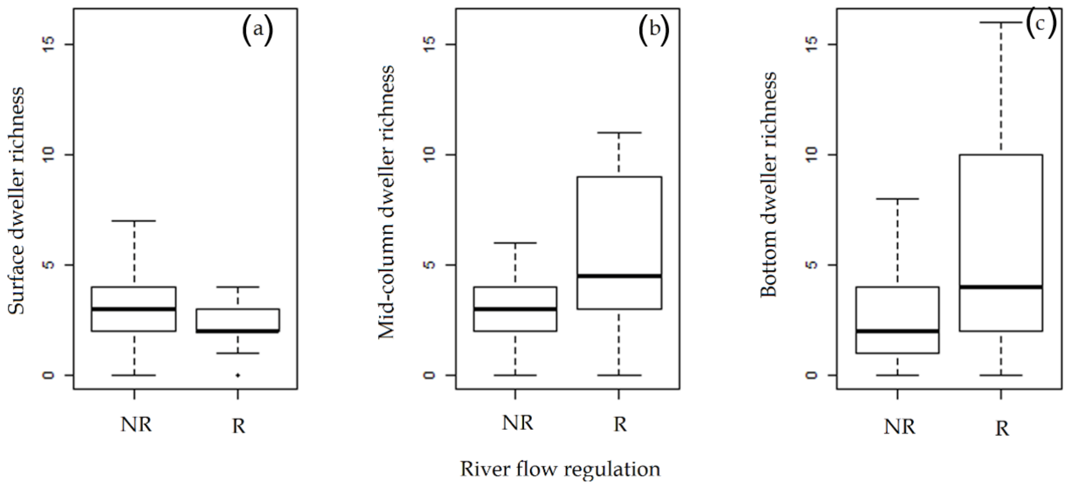

Figure 4. 5. Guild-wise fish species richness in non-regulated and regulated sub-basins. Surface-dwelling guild richness (a) was higher in non-regulated sub-basin, while mid-column (b) and bottom-dwelling richness (c) was lower in non-regulated as compared to regulated sub-basins.

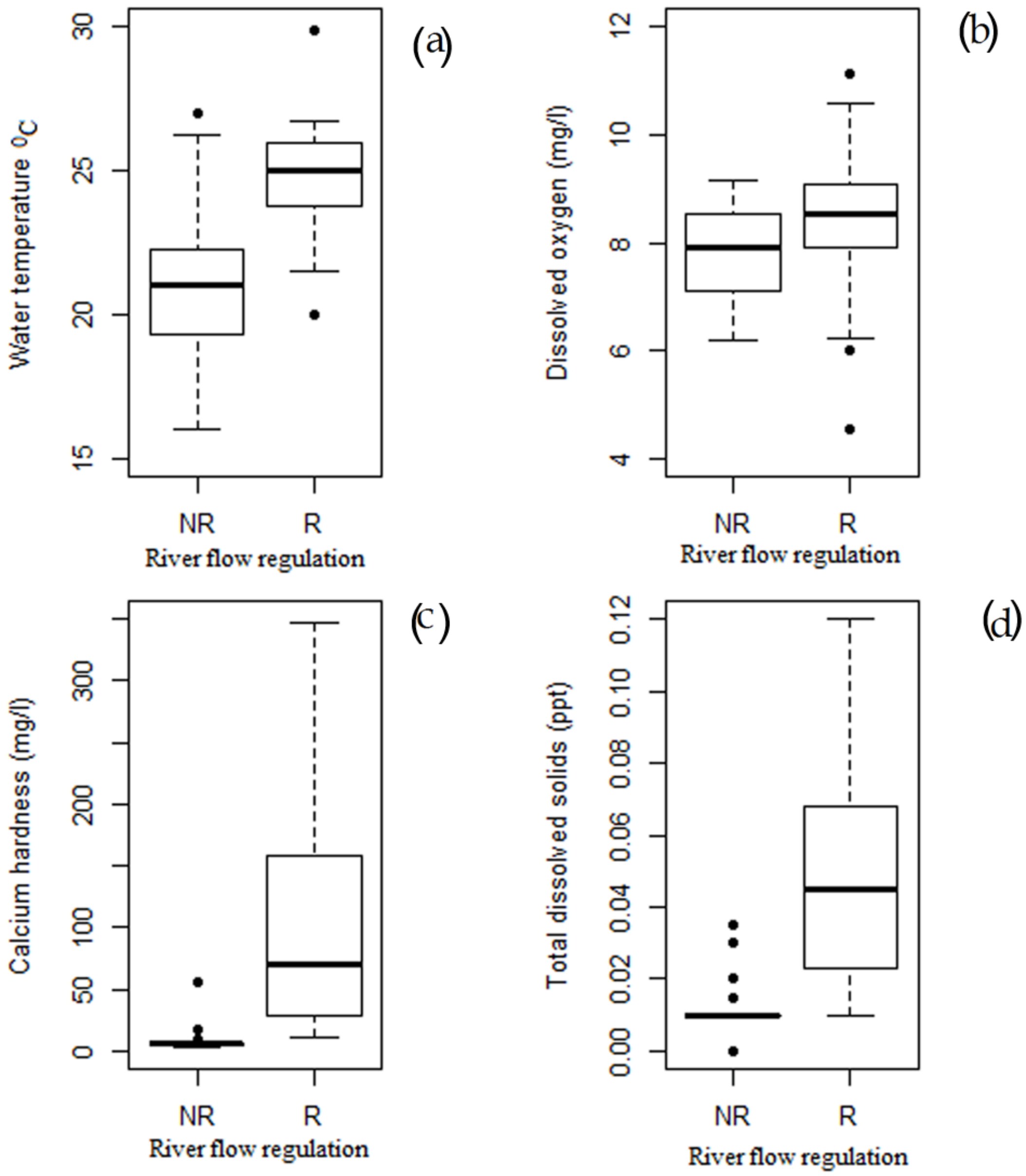

Figure 4. 6: Differences in selected water quality variables between regulated and non-regulated river sub-basins (NR=Non-regulated sub-basin, R=Regulated sub-basin). (a) Water temperature (b) Dissolved oxygen (c) Calcium hardness (d) Total dissolved solids.

Ecological variable selection for regression analyses

Principal component Analysis (PCA) a multivariate statistic technique was used to convert a set of correlated environmental variables into a set of orthogonal, uncorrelated axes called principal components. The first three principal components accounted for 83.03% of the total variation in environmental covariates (Appendix S3 Figure 1). These components were related to stream characteristics i.e. canopy cover (PC1), water quality (PC2) and substrate type (PC3). Total alkalinity (TA), water temperature (WT), total dissolved solids (TDS), dissolved oxygen (DO), electrical conductivity (EC) and pH were correlated strongly with PC2. Based on the PCA loadings I extracted variables such as water temperature, calcium hardness (CH), total dissolved solids, dissolved oxygen, canopy cover, depth-width ratio, and substrate type (% of pebble), to use as independent variables in exploring further regression analyses with guild-wise species richness as response variables (Table4. 2).

Table 4. 2. Comparison of environmental variable values in NRSB and RSB. Statistical significance (***) was obtained for differences in means using a Welch t-test (with unequal variance for groups) [alpha=0.05; p < 0.001***, ^ indicates no significant difference].

Environ variables	Mean (SD)		Welch t-test statistics		
	NRSB	RSB	df	t	p-value
Water temperature (^{0}C)	20.86	24.76	45.2	-8.52	<0.001 ***
	(2.28)	(24.76)			
TDS (mgL^{-1})	0.011	0.052	25.27	-6.15	<0.001 ***
	(0.004)	(0.033)			
Calcium hardness (mgL^{-1})	8.69	110.69	21.16	-4.41	0.0002 ***
	(7.93)	(109)			
DO (mgL^{-1})	7.80	8.35	27.77	-1.28	0.21^
	(0.94)	(1.64)			
Inorganic nitrates (mgL^{-1})	0.17	0.38	23.09	-3.13	0.0046
	(0.08)	(0.29)			

Differences in environmental variables in relation to river regulation and disturbance

Water temperature was higher in regulated sub-basin than non-regulated sub-basin (*df* = 45.2, t =-8.52, p =0.001) and (Table 4. 2, Figure 4. 6) due to the lack of riparian vegetative cover in RSB than NRSB. Calcium hardness (*df* = 21.16, t =-4.41, p =0.002) and inorganic nitrates (*df* = 23.09, t =-3.13, p =0.004) were higher in RSB, indicating poorer water quality due to weathering of rocks (limestone, sedimentary rocks or calcium bearing minerals) and sewage generated from the agricultural and town (Table 4. 2). Total Dissolved Solids (TDS) also followed a similar pattern (*df* = 25.27, t=-6.15, p <0.001), but dissolved oxygen (*df* = 27.77, t=-1.28, p =0.21) did not differ significantly between RSB and NRSB (Table 4. 2, Figure 4. 6). I did not detect any significant differences in water quality variables in relation to local water abstraction.

Effects of environmental variables on guild-wise fish species richness

Responses to environmental variables differed across the three guilds (Table 4. 3). Overall, calcium hardness was negatively correlated and total dissolved solid concentration positively correlated species richness of all guilds. In NRSB, only water temperature positively influenced surface-dwelling fish species richness (Table 4. 3). In RSB, water temperature was positively correlated with species richness of BD and MCD guilds (Figure 4. 5, Table 4. 3). In summary, these results indicated that 1) river regulation influenced fish species richness differentially, by effecting changes in water temperature and water quality, and 2) water quality had a significant influence on fish richness in regulated sub-basins**.**

Discussion

I found distinct differences in fish guild richness, species composition, and presence of endemic species across regulated and non-regulated sub-basins of Mhadei, Malaprabha, Tunga and Bhadra in the WG's of India. Variable effects of flow regulation on different fish guilds were likely mediated by altered water temperature and chemical characteristics (water quality). Surface-dwelling fishes appeared to be affected by flow regulation indirectly through water quality, and their responses were different from mid-column and bottom-dwelling fishes. Water temperature was lower in NRSB compared to RSB, it is likely that SD fish richness increased till an upper limit, but declined at even higher temperatures (in RSB). For BD and MCD guilds, higher temperatures in RSB were perhaps more suitable. Surface-dwelling rheophilic and opportunistic fishes are known to require run-riffle habitats with good water quality in floodplain rivers for spawning (Costa et al., 2013; Borges and Araujo, 2013; Winemiller and Jasper, 1998). As a result, their lower richness in regulated sub-basins might be due to the combined effects of temperature and water quality. The amount of total dissolved solids (TDS), both in RSB and NRSB, was positively correlated with

Table 4. 3. Selected Generalized Linear Models (GLMs with Poisson errors) showing effect sizes of environmental variables on guild-wise species richness in all sub-basins, and for RSB and NRSB. (Sub-basins: RSB=regulated, NRSB=non-regulated; Variables: TDS=total dissolved solids, CH=Calcium hardness, WT=water temperature, DO=dissolved oxygen). Delta AIC values indicate improvement brought in fit by GLM over null (intercept-only) model. In case of MCD species richness in NRSB, no model was found to improve fit over the null model.

Guild	Sub Sub-basin	WT Estimates (SE)	CH Estimates (SE)	TDS Estimates (SE)	DO Estimates (SE)	Mac-Fadden's Pseudo R^2	AIC	Delta AIC (w.r.t null model) --
SD	All	-	-0.006 (-0.001) **	-	-	0.24	199.63	217.2
	RSB	-	-	40.94 (18.48) - TDS^2 -289.90 (139.76)-		0.40	80.445	1.315
	NRSB	0.06 (0.02)*	-	-	-	0.09	321.57	10.51
MCD	All	-	-0.02 (0.001)·	12.03 (1.92) ***	0.15 (0.05)*	0.62	153.2	396.8
	RSB	0.12 (0.04) **	-0.009 (0.001) ***	-	-	0.74	91.44	76.43
	NRSB	-	-	-	-	-	null model	
BD	All	0.081 (0.03) **	-0.003 (0.001) **	10.18 (1.80) ***	-	0.44	253.33	333.2
	RSB	0.14 (0.03) ***	-0.006 (0.001) ***	-	-	0.52	113.37	60.07
	NRSB	0.05 (0.03).	-	-	-	0.07	335.37	9.95

Statistical significance, alpha = 0.05: (p values * p <0.05, ** p <0.01, *** p <0.001).

BD and MCD guilds, but showed a quadratic relationship with surface-dwellers indicating that the SD guild was more sensitive to TDS than BD and MCD.

Water quality might decline after regulation due to changes in local land uses, human disturbance, or intensification of cropping patterns, as was observed in the study area (Heller et al., 2012). Poorer water quality could have also affected some endangered rheophilic fishes such as *Tor* sp, *Barilius* sp, and *Hypselobarbus* sp (field observations). Further, fishes with deformities were recorded only from RSB and never from NRSB (field observations). Lower water releases in RSB could have aggravated pollution impacts by not allowing adequate dilution or flushing of pollutants. NRSB river segments supported the persistence of many endemic and specialized fishes such as *Balitora* sp, *Barbodes* sp, *Batasio* sp, *Rohtee* sp etc. that were not detected in RSB. The consistently poorer water quality indicators in regulated sub-basins emphasized that monitoring of water quality as part of ecological flow regime maintenance which will be essential for the persistence of fish species impacted by river regulation.

My study could not detect any direct responses in terms of fish species richness to local water abstraction, for any of the guilds studied. Although certain specific effects are likely on fish abundance due to local changes in stream substrate, pollution sources, and minor disturbances for household uses of water. These effects could not be unraveled by this study for species richness. Future studies might thus need to look at effects of local disturbances on fish abundance and turnover than only on species richness.

I chose water column position-based guilds of fishes to examine their responses to flow regulation and associated environmental characteristics. This choice appeared to overcome potential redundancies in other guild classifications (e.g. fish communities dominated by omnivores), while still retaining correlations of fish position with other life-history strategies (particularly in reproductive guilds and sensitivity to flow alterations). Based on the exploratory analyses, I advocate the use of formal methods such as ordination for selecting appropriate guilds for analyzing fish species responses to regulation, based on available data.

Overall, the results matched with reported impacts of flow regulation on fish species. For instance, in the Teesta and Bhadra rivers in India, Connecticut stream in USA and few northern European large rivers, surface-dwelling rheophilic fishes were less abundant in regulated basins whereas eurytopic fishes in mid-column and bottom-dwelling guilds may have benefitted (David, 1956; Aarts and Nienhuis, 2003; De Leeuw et al., 2007; Chakrabarty and Homechaudhuri, 2013; Macnaughton et al., 2016). I observed that flow regulation modified connected river habitats to disconnected pools, which might have led to the above observations. The discrete fish guilds did not allow me to interpret a clear continuum in life-history strategies utilized by fishes as shown in previous studies from American rivers (Winemiller et al., 1989; 1992), but nonetheless helped detect broad differences. Studies on assessing the impact of dams on fish communities in rivers across South Asia have suggested that the dam causes considerable decline in native species by obstructing their seasonal spawning migrations (Jackson and Marmulla, 2001; Larinier, 2001; Hoeinghaus et al., 2009; Gopal, 2013). Upstream migration of surface-dwelling, rheophilic fishes such as *Tor khudree*, *Hypselobarbus jerdoni* and *Cirrhinus fulungee* could be affected due to hydrological barriers. Effects of existing barriers on changes in native fish breeding patterns also need to be studied in detail (Larinier, 2001).

River regulations due to barriers have disconnected river habitats by encouraging intensive gravel and sand mining and water abstraction in some segments especially during low water levels, this could have enhanced the water temperature. The relative contribution of surface water to ground-water to downstream flow is likely to decrease downstream of the barriers which may result in change in water quality such as increase in calcium hardness and temperature (Wurts and Robert, 1992; Hunse, 2007; Malkhede, 2003). The guild composition in such segments was dominated by bottom-dwelling fishes that appeared tolerant to river regulation. Land-use changes associated with the construction of an inter-basin water canal, road constructions, and check-dam constructions in the RSB might also have increased sediment deposition in headwater reaches, likely affecting potential habitat for endemic fishes. Some endemic species such as *Bhavania australis* were observed in the upper reaches of Mhadei sub-basin (pers. comm. Vijay Mohan Raj) but not in the upper reaches of Malaprabha due to loss of headstream habitat near the canal construction site. Siltation and reduction in dissolved oxygen is also known to affect some sensitive fish species (*Bhavania* sp, *Balitora* sp), which reproduce in highly oxygenated benthic habitats (Ganasan and Hughes, 1998). Individual fishes with deformities and disease were recorded only in the Malaprabha river. I also observed that construction of check dams and barrages in the Malaprabha basin, over time, resulted in local fishing communities having to travel upstream for about 30-40 km daily to meet their subsistence requirements, suggesting wider impacts of declines in fish abundance, which need further detailed study.

Implication for conservation of fish diversity in the Western Ghats

This study contributes to the understanding of broad ecological responses of fish guilds, based on their position in the river water column, to changes in water quality due to effects of river flow regulation (Winemiller, 1989). Importantly, the study identified that regulated river sub-basins had poorer quality of river water (e.g. increased level of calcium hardness and total dissolved solids, etc.) that led to negative effects on surface-dwelling fishes. Future threats such as inter-basin water transfers (an head-water link between the Malaprabha and Mhadei) are likely to therefore cause further reduction in water quality and seriously affect freshwater fish diversity and endemic species in particular (Lynch et al., 2011; Konar et al., 2013; Araujo et al, 2015; Sa-Oliveira et al., 2015). The WG region is the second highest in dam densities in India and more than 352 small to medium hydropower projects (< 25 MW) are under consideration in the Karnataka state alone which will threaten river biodiversity significantly (*Dandekar, P., pers.comm).* However the impacts of local disturbance on fish guild richness in this study appeared equivocal. These results can help generate specific hypotheses to be tested in future assessments fish responses (abundance) to flow alterations and local disturbance in tropical river systems. They also highlight the potential of identifying and maintaining ecological flow regimes to improve water quality not only for fish fauna but also for local human users of water.

The WG's region shows a trend of rapid urbanization and human population pressures are likely to cause further river regulation in the near future (McDonald et al., 2011; Konar et al., 2013). I hypothesize that in future, the modified flow regulation and water pollution effects below the barriers are likely to change thermal regime and water quality affecting sensitive fish guilds in the tropical river systems. With these imminent pressures in mind, catchment-scale conservation planning to protect endemic and endangered fish species needs to prioritize water quality improvement by emphasizing at-source treatment of pollutants and providing adequate flows downstream of barrages and dams, to reduce pollution effects. Freshwater conservation planning and policy in the current scenario of river regulation in the WG's could benefit from this study both to mitigate impacts of existing river barriers and to assess ecological flow requirements for sensitive fish species.

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Chapter 5

Assessing the recovery of fish assemblages downstream of hydrological barriers in India's Western Ghats

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Assessing the recovery of fish assemblages downstream of hydrological barriers in India's Western Ghats

Introduction

Anthropogenic flow regulation and the resulting fragmentation of stream and river habitats is a major threat to conservation of freshwater fish species worldwide (Bunn and Arthington, 2002; Mamqvist and Rundle, 2002; Nilsson et al., 2005; Dudgeon, 2010; Vorosmarty et al., 2010). Downstream impacts of 'river barriers' such as dams, barrages, and so-called 'run-of-river' hydropower projects are often severe for tropical fish communities (Pringle, 2001; Pandit and Grumbine, 2012; Anderson et al., 2006, Brown et al., 2013). Presence of barriers might thus affect fish recovery at different spatial extents and scales within their catchments (Dudgeon, 2011). Flow alterations not only reduce stream discharge needed to maintain fish abundance and diversity downstream of barriers, but can also induce fluctuations and disturbances, to natural flow regimes downstream, causing habitat loss, mass mortality, and eventual local extinction (Travnichek et al., 1995; Bunn and Arthington, 2002; Phomikong et al., 2015). Despite the well-documented threats from these interventions (Pringle, 2001; Hoeinghaus et al., 2009; Dudgeon, 2010; Sakaris, 2013), the potential for ecological recovery of fish communities below barriers, and the biotic and abiotic factors contributing to recovery, are not well understood (Ellis and Jones, 2013), in part due to lack of empirical data, especially for species rich tropical rivers.

Regulated rivers are distinctly different in their ecological processes when compared to natural, free-flowing rivers. Theoretically, this difference has been attributed to hydrological connectivity in free-flowing rivers - the 'River Continuum' concept; Vannote et al (1980) by which natural gradients in species composition and community structure of aquatic organisms are maintained. In contrast, in regulated rivers, habitat diversity resulting from discontinuities in the river flow determines spatial turnover in fish diversity, as understood by the 'Serial Discontinuity' concept (Ward and Stanford, 1995). The concept proves especially useful in understanding processes of recovery following disruptions in longitudinal and lateral connectivity caused by human-made river barriers (Ellis and Jones, 2013). Further work attributes a greater role to functional processes (Thorp et al., 2008) in locally unaltered habitat nodes within the larger modified catchment or stream network, especially as the distance from the barriers increases and the impact of flow impairment reduces. Beyond certain distance thresholds, basin-level hydrological connectivity might improve, and thus allow some stretches to return to near-natural baseline conditions where species might persist (Connell and Sousa, 1983). In addition, some species' life-history traits may be more resilient to flow alterations than others, and their potential for recovery could be higher than sensitive species.

Central to the identification of factors enabling recovery is understanding the complex and nonlinear relationships between river flow regimes, habitat quality, and responses of fish biodiversity (Taylor et al., 2014; King et al., 2015; Macnaughton et al., 2015). Kubach, Scott and Bulak (2011) reported recovery in fish assemblages after a 52-month period following an oil spill in the Reedy River in USA, indicating that recovery might be observed after long time-lags, rather than being determined by only spatial location effects. The persistence of fluvial specialists (rheophilic fishes with high swimming ability) downstream of dams is generally considered as an important part of recovery (Travnichek et al., 1995). Increase in depth and discharge downstream is also known to contribute to recovery of rheophilic species, the strength of recovery typically increasing with downstream distance from the barrier (Scheidegger and Bain, 1995; Stoll et al., 2014; Piller and Geheber, 2015). Though overall fish species richness increases downstream (Ibañez et al., 2009), this is purely due to spatial turnover: rheophilic species are replaced by eurytopic species that are well adapted to lentic habitats formed by flow reduction (Scheidegger and Bain, 1995; Aarts and Nienhuis, 2003). Recovery might also be affected by topographic factors, land-use in the catchment, or other human disturbances such as pollution and water abstraction (Jackson et al., 2001a; Schlosser, 1991). As a result, separating the effect of species replacement (turnover) from recovery, while examining patterns in species community composition, is important (Kubach et al., 2011). More recent studies have focused on the contribution of undammed downstream tributaries to functional connectivity and ability of fish species with different life-history traits to recover below large barriers (Brown and Ford, 2002; Alexandre et al., 2013). Fish swimming ability and movement are key determinants of recovery, as they directly influence how and whether fish can negotiate barriers when dam/barrage gates may be opened (e.g. during seasonal flooding) to travel upstream or downstream (Rolls and Sternberg, 2015).

Studies on fish recovery are relatively few from tropical South Asia, despite the high density of and intensive river flow regulation by existing and under-construction dams, barrages, and hydropower projects on rivers (Bhat and Magurran, 2007; Pandit and Grumbine, 2012; Theophilus, 2014). In this chapter, I study the ecological processes contributing to fish species recovery below large barrages (height > 2 m, width 50-150 m, and > 10 km^2 impoundment area) and small barriers (small barrages and check-dams =< 2 m, < 50 m width and < 1.5 km^2 impoundment area) in the upper catchment of the Malaprabha River of the WG's of India. There have been recent inter-state conflicts over water sharing through inter-basin transfers in this river basin, and demands are intensifying. As a result, conservation planning for freshwater taxa needs to be prioritized in this eco-region. In this regard, studies on fish responses to flow regulation can help assess the cumulative impacts of current and future water developments on regulated stream networks.

Here, I assess the potential for recovery of native fish assemblages downstream of river barriers. For this I define 'recovery' as the similarity in fish community composition as compared to the composition in undammed reaches upstream of all barriers within the basin. I hypothesize that the presence of undammed streams joining rivers downstream of barriers will have an amelioration effect and positively influence species recovery. Based on this hypothesis, I ask two broad questions: (1) what is the potential for species recovery below barriers? (2) what river habitat characteristics are likely to influence spatial patterns in recovery (correlated with downstream distance from barriers)? As per the Serial Discontinuity Concept (Stanford and Ward, 2001), I predict that similarity in species composition will 1) reduce initially, and 2) increase subsequently with increasing distance from the barrier, owing to undammed tributaries joining downstream (Fig. 5.1a, b). Finally, I discuss implications of fish recovery for aquatic conservation planning, restoration of river habitats, and planning ecological flow regimes in regulated river basins of the WG.

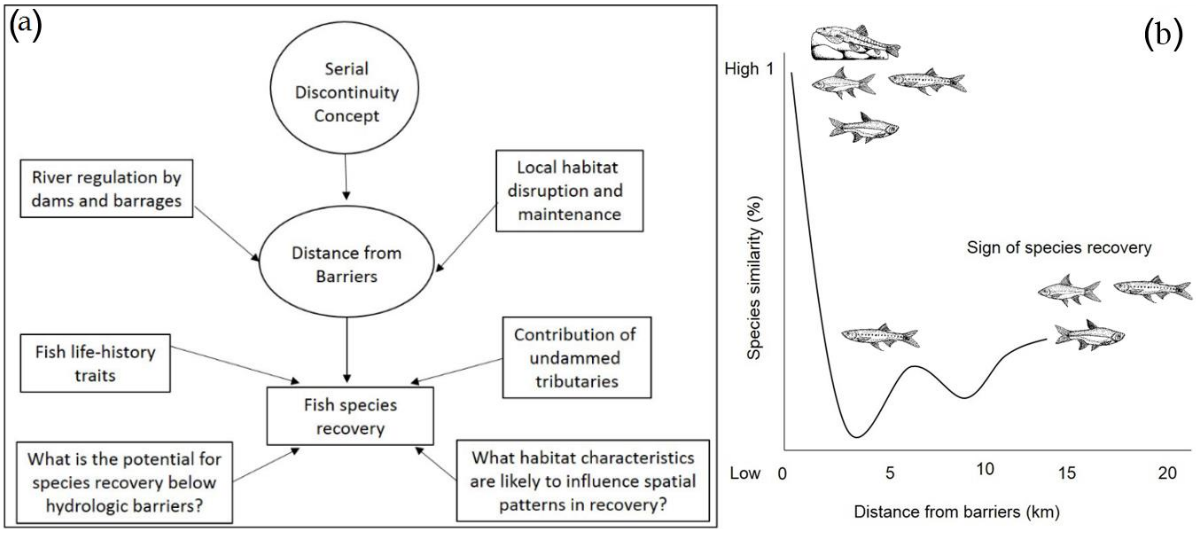

Figure 5. 1. (a) Schematic showing the application of the Serial Discontinuity Concept (SDC) in arriving at the hypotheses tested in our study. (b) Expected pattern of change in species recovery with increasing distance downstream of barriers.

Materials and Methods

Study Site

The Central and Southern WGs of India have high freshwater fish diversity and endemism (Bhat, 2004; Raghavan et al., 2008; Molur et al., 2011). The east-flowing Malaprabha river originates from Kankumbi in the central WG in the state of Karnataka, India (Fig. 5. 2). Annual rainfall recorded in the Malaprabha ranged from 2000 to 3500 mm and mean discharge from 1000 to 2300 m/s (Jha & Singh, 2008). An overall negative trend in discharge was noted post-regulation, despite no appreciable reduction in rainfall, suggesting the potential for regulation impacts on fish guild structure (V. Atkore, unpublished data). The main land-use types in sub-basin are forests and agriculture with sugarcane, sunflower, and paddy as the main crops. Water abstraction by pumps, illegal sand/boulder mining, pollution, and destructive fishing methods are also intensifying threats in the basin. The river is highly regulated by barrages and check-dams, used both for irrigation and domestic purposes. I identified 10 (1 large, 9 small) barriers in the upper catchment of the basin (> 500 m ASL elevation), (Table 5. 1). An inter-basin link between the Malaprabha and Mhadei river (a west flowing river) has affected some of the crucial riparian habitats for stream fishes in the headwater reaches (Atkore et al., 2012).

Table 5. 1. Site-wise details on locations of barriers, cumulative impacts and number of undammed tributaries present between segments and their nearest upstream barriers.

River Segment	Coordinates Lat. Long.	No. of barriers (small, large)	Distance from nearest upstream barrier (km)	Cumul. impact	No. of. undam. tributar.
Habbanhatti	15.71N, 74.35E	1, 0	0.29	3.45	0
Kusmali	15.71N, 74.37E	1, 0	4.70	0.2	1
Olmani	15.71N, 74.40E	1, 0	8.82	0.07	2
Shankerpeti	15.68N, 74.42E	4, 0	4.40	0.16	3
Malavi	15.65N, 74.43E	4, 0	0.12	25	0
Asoga	15.62N, 74.47E	5, 0	0.22	8.82	0
Shedegali	15.62N, 74.49E	6, 0	2.91	1.23	0
Rumewadi	15.63N, 74.51E	6, 1	0.53	0.78	0
Kupatgiri	15.63N, 74.53E	6, 1	2.30	0.57	1
Katgali	15.71N, 74.47E	1, 0	0.05	20	0
Valmiki	15.71N, 74.45E	1, 0	2.06	0.47	1

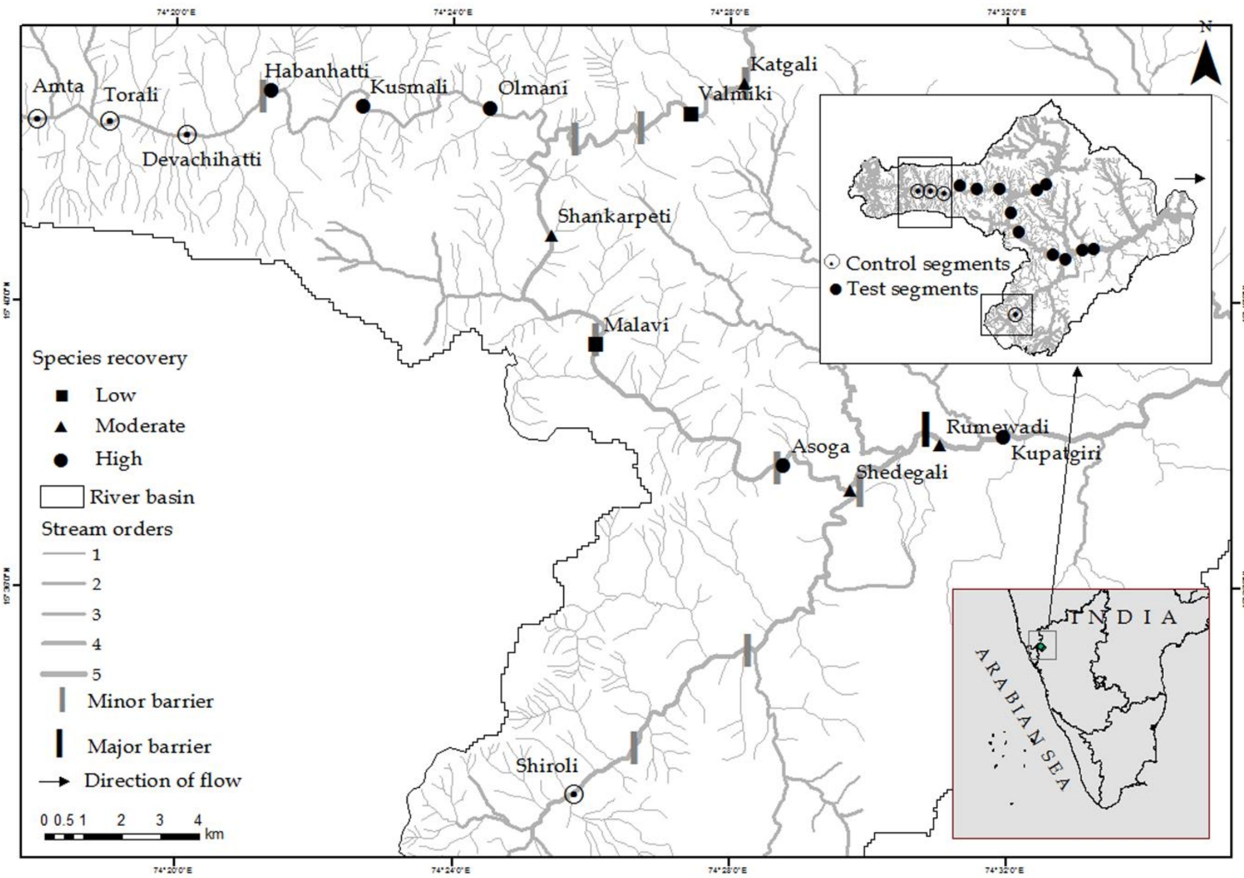

Figure 5. 2. Map showing fish species recovery (shown for total fish species) in the Malaprabha basin. Locations of upstream control segments (unregulated reference sites) and segments downstream of barrier (test segments) are shown in the inset.

Sampling strategy

In this study I defined ‘river regulation’ mainly with reference to ‘large barriers’ (i.e. barrages), and ‘small barriers’ (i.e. temporary impoundments, small barrages, check dams) in the basin. I assessed patterns of spatial recovery and identified potential factors influencing recovery for total fish species richness and endemic fish species richness. I defined species recovery as being strictly downstream of these barriers, which I compared against a ‘reference composition’ derived from occurrence data only for species that were recorded in upstream control sites (river segments) that were not influenced by any barriers. A river segment (150 m long) was the sampling unit and a total of 15 segments were sampled, including 4 upstream control segments and 11 segments downstream of large and small barriers (Table 5. 1). I calculated stream order of the segments from a GIS map made by digitizing streams from Survey of India topographical maps with scale 1: 50,000. I also controlled for effects of elevation on species turnover by choosing all sites in the same elevation range. Both upstream and downstream segments mainly included river pool habitats, and had similar elevational extents (mean 693 ± SD 26 m) and stream orders (2-4). As background variables were similar, the upstream-downstream comparisons were justified and allowed for testing the specific impacts of river regulation by barriers. I restricted sampling to pools because these were the only habitat type consistently available for sampling, due to effects of dewatering and flow regulation.

Between the years 2011 and 2014, I sampled fishes using 0.5 cm x 0.5 cm and 1.1 cm x 1.1 cm mesh sized cast nets, using replicate casts to calculate species accumulation. Cast nets have been widely used for other studies in the WG and are known to be suitable for sampling different fish guilds in hill-stream sections (Bhat, 2004; Abraham and Kelkar, 2012). In addition, two visual transects were conducted along each segment to detect easily visible species on the surface and mid-column. Cast netting effort combined with visual records was deemed adequate for sampling all major fish guilds, i.e. feeding, positional, reproductive and flow dependent guilds (Welcomme et al., 2006) regardless of relative abundance (V. Atkore, unpublished data). About 80% of the species reported from the upper catchments of the Krishna river Basin (Rema Devi et al., 2013) were sampled in my study, indicating adequate sampling effort.

Environmental variables describing stream habitat and water quality characteristics were measured for each segment. I recorded depth and channel width (m) of the stream manually using tape measures. I visually classified stream substrate and estimated percentages of different sediment categories (rocks, boulders, pebbles, cobbles, sand, and clay) for each segment at 3 locations along the stream length and averaged the percentage of each category later. Temperature was measured using a handheld thermometer. I measured different water quality variables in the field as follows, using standard estimation procedures as described in (APHA, 2005). 1) Dissolved Oxygen (DO) was measured using Winkler's method 2) pH and electrical conductivity were measured using hand-held meters (HI98130 and HI98303), and 3) total alkalinity, calcium hardness, concentration of inorganic nitrates, phosphates, and chlorides were measured using laboratory analyses as prescribed by reference manuals of APHA (2005). Further, I derived an index of human disturbance level based on observed activities along the sampled segment (e.g. fishing, sand/boulder mining, domestic uses, pollution etc.). I used field surveys and GIS maps to spatially record the presence of adjacent undammed streams (tributaries) for each segment. I measured the exact downstream distance of the segment from the nearest large or small barriers in a GIS system. The 'cumulative impact' of these upstream barriers was scaled as the number of barriers per km of downstream distance from the nearest barrier (Table 5. 1). These variables were used as ecological predictors to test our hypotheses about fish species recovery (response variable).

Statistical Analysis

For analysis, I first calculated the fish community similarity, i.e. the proportion of species occurring downstream of barriers, out of the total species and endemic species richness recorded in upstream control sites. I classified recovery into three levels: 1) low (< 0.33), 2) moderate (0.34-0.66) and 3) high (0.67-1.00). I used boxplots and scatter-plots to explore how species recovery changed with downstream distance of segments from barriers. I then used non-linear regressions to model the pattern of species recovery as a function of increasing downstream distance from barriers. I compared two types of non-linear models that reflected different predictions about how recovery was expected to increase: 1) recovery immediately rises to the highest possible after a threshold distance (asymptotic exponential model), and 2) recovery continues to increase at a different rate after the threshold distance (logistic model).

Asymptotic exponential models were of the form $y = a \times (1 - e^{-b*Distance})$, and logistic models had the form $y = a/(1 + e^{\frac{(b-Distance)}{c}})$ where y = total or endemic species recovery, and Distance = downstream distance from the barrier, and a, b, c were model parameters governing the shape of the function. No transformation of variables was required for parameter estimation. Model comparisons were based on how well the predicted and observed values corresponded (visual estimation of fit), and a statistical measure of fit (residual standard error of models) (Crawley, 2007). The Akaike Information Criterion (AIC) was used to guide model selection based on fit and parsimony, and simpler models were selected. All analyses were conducted in the R software package 'nlme' (R Core Team 2013). Recovery was assessed at two distance thresholds, one based on the median distance (2 km) for segments downstream from barriers, and at a greater arbitrarily determined threshold of 5 km. I qualitatively assessed if the presence of undammed tributaries joining the impaired main stem of the river improved fish recovery. I then ran Spearman's rank correlation tests to assess how stream characteristics (water quality, stream morphology, etc.) correlated with downstream distance from barriers, and fish recovery. Life-history traits and habitat preferences of fish species were compiled from literature sources, to discuss what traits made them more or less able to recover post river regulation (Daniels, 2002; Albanese et al., 2009).

Results

I sampled 28 species in the upstream control sites (n = 4) of the Malaprabha sub-basin, of which 14 were WG endemics (details in Table 5. 2). Bottom dwelling species were dominant (46.42%) followed by mid-column (32.14%) and surface dwelling species (21.42%) (Table 5. 2). The fish species monitored in the study were mainly rheophilic, periodically breeding, rock- or plant-spawners (Table 5. 2). Observed spatial patterns of fish community similarity (recovery) confirmed the hypothesis that recovery was low immediately downstream of barriers, and increased with increasing downstream distance (Fig. 5. 1, 5. 2). These patterns were consistent for endemic fish richness and for total fish species richness sampled in the upstream control sites (Fig. 5. 3a, 3b).

Recovery was negatively correlated with the number of upstream large and small barriers (scaled to barriers per km) in the sub-basin, indicating their cumulative impacts (Fig. 5. 3c, Table 5. 1). Total species recovery was positively correlated with dissolved oxygen (Spearman's rho = 0.84, p = 0.004) and rocky stream substrate (Spearman's rho = 0.65, p = 0.028). Similarly, endemic species recovery was positively correlated with dissolved oxygen (Spearman's rho = 0.93, p = 0.0002), water temperature (Spearman's rho = 0.57, p =0.64), and rocky substrate (Spearman's rho = 0.71, p = 0.014). Total (Spearman's rho = -0.65, p = 0.03), and endemic species recovery (Spearman's rho = -0.59, p = 0.05) were negatively correlated with total alkalinity. Of these, dissolved oxygen and total alkalinity respectively increased and decreased with distance from barriers (Fig. 5.3e, 3f). Water temperature and rocky habitat showed no correlation with distance from barriers (temperature: Spearman's rho = 0.03, p = 0.92; rocky habitat: Spearman's rho = 0.27, p = 0.40). The number of undammed tributaries (of stream order >= 3) downstream of barriers positively influenced recovery of species, as expected (Fig. 5. 3d). Both total and endemic species recovery increased to the highest level after a distance of 2 km downstream of barriers, as per the predictions of the non-linear asymptotic exponential models. Parameter estimates, model fit and selection criteria are given in Table 5. 3.

Out of 28 species, 26 recovered downstream of barriers, and two species did not. Till 2 km downstream, 24 species (85.7%) reappeared, of which 13 endemics out of 14 were recorded. Till the 5 km threshold, 25 out of 28 fish species (89.3%) with 13 endemics, were recorded. High levels of recovery were observed for most fish species that we monitored in the study, but no clear associations were noted with any particular guilds. Fishes that showed low recovery were typically with low swimming ability and benthic habitat preferences. These species included the loaches *Nemacheilus thermalis* and *Paracanthocobitis mooreh*, the catfish *Clarias batrachus*, and carps *Hypselobarbus dobsoni* and *Chela cachius*.

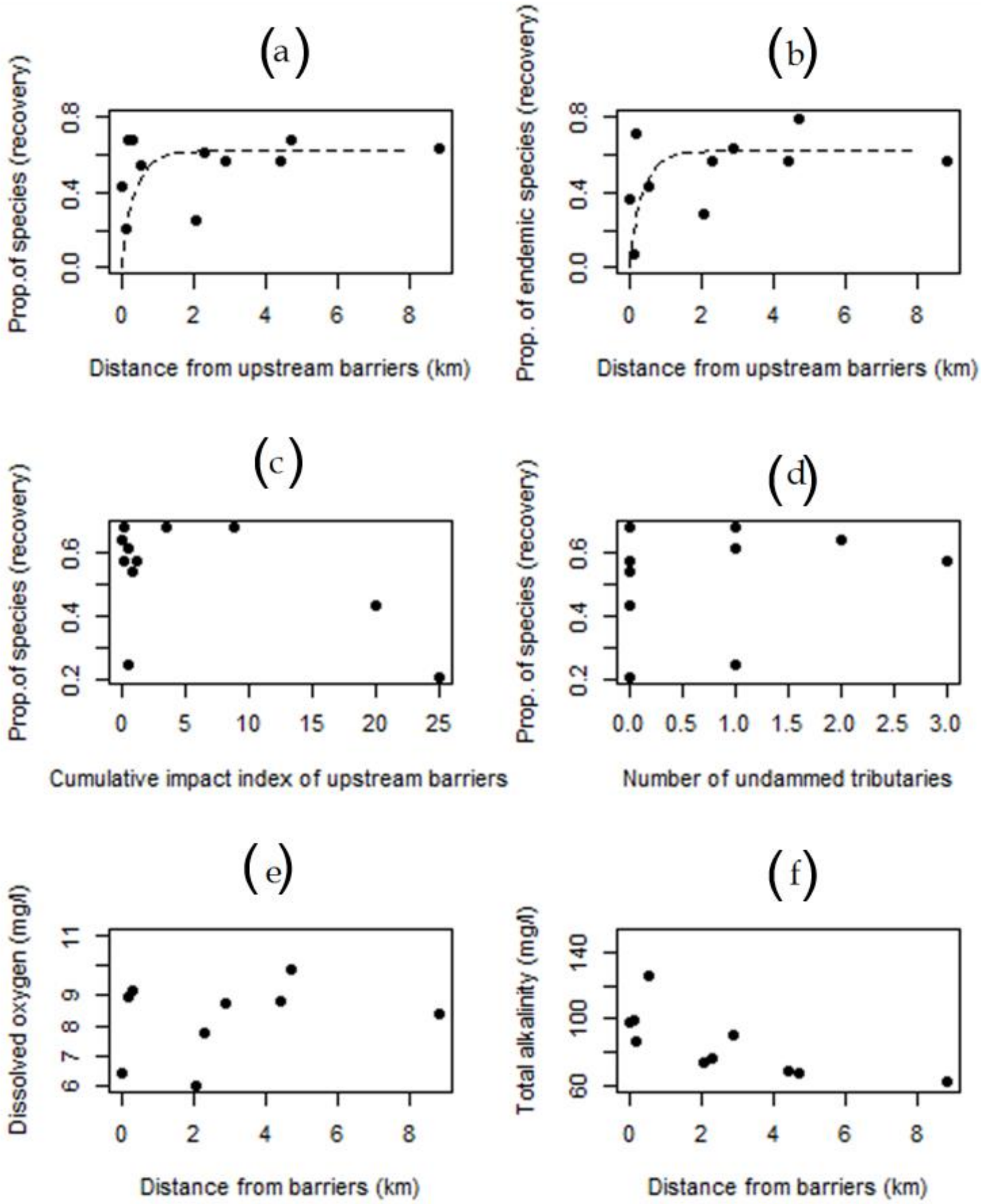

Figure 5. 3. Increase in (a) total and (b) endemic fish species recovery with increasing distance from upstream barriers; reduction in recovery (c) at higher levels of cumulative impact (number of upstream barriers/ downstream distance in km) and improvement in species recovery with the number of undammed tributaries joining the river below barriers (d). Dissolved oxygen (DO) (e) increased with distance from barrier, and total alkalinity (f) reduced with distance from barrier.

Table 5. 2. Species sampled in the study area, occurrence up to 2 and 5 km distances downstream of barriers, with life-history traits and recovery levels.

Fish species (*Order*, Family)	Distance thresholds		Guild classifications						
	2 km	5 km	Position in water column	Flow preferences	Diet	Swimming ability	Life-history strategy	Reproduction-based	Recovery Level
Cypriniformes **Cobitidae**									
*Paracanthocobitis mooreh**	1	0	Bottom	Rheophilic	Heterotrophic	Low	Periodic	Lithophils	Low
*Nemacheilus thermalis**	1	1	Bottom	Rheophilic	Phytophagous	Low	Periodic	Lithophils	High
Cyprinidae									
Cirrhinus fulungee	1	1	Surface	Rheophilic	Omnivore	High	Periodic	Lithophils	High
Chela cachius	0	0	Surface	Rheophilic	Omnivore	Moderate	Periodic	Phytolithophils	Low
*Devario malabaricus**	1	1	Surface	Rheophilic	Heterotrophic	High	Opportunistic	Phytolithophils	High
*Garra bicornuta**	1	1	Bottom	Rheophilic	Phytophagous	Moderate	Opportunistic	Lithopelagophils	High
*Garra mullya**	1	1	Bottom	Rheophilic	Phytophagous	Moderate	Opportunistic	Lithopelagophils	High
*Garra stenorhynchus**	1	1	Bottom	Rheophilic	Phytophagous	Moderate	Opportunistic	Lithopelagophils	High
Hypselobarbus curmuca	1	1	Bottom	Rheophilic	Omnivore	High	Periodic	Phytophils	High
*Hypselobarbus dobsoni**	0	1	Bottom	Rheophilic	Phytophagous	High	Periodic	Lithophils	Moderate
*Osteochilius nashii**	1	1	Mid-column	Rheophilic	Omnivore	High	Periodic	Lithophils	High
*Pethia setnai**	1	1	Mid-column	Rheophilic	Heterotrophic	Moderate	Intermediate	Phytophils	High
Pethia ticto	0	1	Mid-column	Eurytopic	Omnivore	Moderate	Periodic	Phytophils	Moderate
*Puntius amphibius**	1	1	Mid-column	Rheophilic	Heterotrophic	Moderate	Intermediate	Phytophils	High
Puntius sophore	1	1	Mid-column	Eurytopic	Heterotrophic	Moderate	Periodic	Phytophils	High
Rasbora daniconius	1	1	Mid-column	Eurytopic	Heterotrophic	High	Opportunistic	Phytophils	High
*Rasbora labiosa**	1	1	Mid-column	Eurytopic	Omnivore	Moderate	Opportunistic	Phytophils	High
Salmophasia bacaila	1	1	Surface	Limnophilic	Omnivore	High	Periodic	Phytophils	High
Salmophasia boopis	1	1	Surface	Limnophilic	Heterotrophic	High	Periodic	Phytophils	High
*Salmophasia novacula**	1	1	Surface	Limnophilic	Heterotrophic	Moderate	Periodic	Phytophils	High

Fish species (*Order*, Family)	Distance thresholds		Guild classifications						
	2 km	**5 km**	**Position in water column**	**Flow preferences**	**Diet**	**Swimming ability**	**Life-history strategy**	**Reproduction-based**	**Recovery Level**
Systomus sarana	1	1	Mid-column	Limnophilic	Phytophagous	High	Intermediate	Phytophils	High
*Tor khudree**	1	1	Mid-column	Rheophilic	Omnivore	High	Periodic	Lithophils	High
Siluriformes **Bagridae**									
Mystus bleekeri	1	1	Bottom	Eurytopic	Heterotrophic	Moderate	Equilibrium	Phytophils	High
Mystus cavasius	1	1	Bottom	Rheophilic	Heterotrophic	Moderate	Periodic	Phytophils	High
Mystus gulio	1	1	Bottom	Rheophilic	Heterotrophic	Moderate	Periodic	Phytophils	High
*Mystus keletius**	1	1	Bottom	Rheophilic	Heterotrophic	Low	Periodic	Phytophils	Low
Clariidae									
Clarias batrachus	0	0	Bottom	Eurytopic	Omnivore	Moderate	Opportunistic	Phytophils	Low
Siluridae									
Ompok bimaculatus	1	1	Bottom	Eurytopic	Heterotrophic	High	Periodic	Polyphils	High

Key: * Fish species endemic to the Western Ghats (Dahanukar & Raghavan, 2013; Daniels, 2002). Guild classifications are based on Daniels 2002, Welcomme *et al*., (2006), and Albanese *et al*., (2009). Flow preferences: Eurytopic=all life stages occur both in lotic and lentic waters, Limnophilic=all life stages confined to lentic water with macrophytes, Rheophilic=all life stages are confined to river flows in main channel. Diet: Heterotrophic=carnivores and insectivores, Phytophagous=algal, plant, and detritus feeders, Omnivores=both plant and animal matter is fed on. Life-history strategies: Equilibrium=fishes with high parental care and juvenile survival with intermediate maturation periods, Opportunistic=early maturing fishes with continuous reproduction but low fecundity, Periodic=large fishes with late maturation, high fecundity, and low juvenile survival, Intermediate=small fishes with prolonged and distinct seasonal reproduction. Reproduction-based guilds: Lithophils=rock/gravel spawners, Lithopelagophils=rock, gravel spawners with pelagic larvae, Phytolithophils=non-obligatory plant spawners, phytophils=obligatory plant spawners, Pelagophils=pelagic spawners, polyphils=no substrate preferences, and psammophils=sand spawners. Recovery level: Observed occurrence patterns categorized into High, Moderate, and Low categories.

Table 5. 3. Non-linear regression model used to model fish recovery as a function of downstream distance from barriers. Total and endemic fish recovery was characterized as rising immediately after a minimum distance threshold, as predicted consistently by the asymptotic exponential models. The chosen models are highlighted in bold.

Response variable	Models compared	Parameter estimates	Residual Standard Error, df	AIC
Total species recovery	**Asymptotic exponential**	**a 0.57 (SE 0.06); p < 0.0001*** **b 2.63 (SE 0.64); p = 0.0025***	**0.16,** df = 9	**-4.81**
	Logistic	a 0.81 (SE 1.85); p = 0.67 b -3.03 (SE 27.15); p = 0.91 c 7.90 (SE 43.94); p = 0.86	0.18, df = 8	-2.51
Endemic species recovery	**Asymptotic exponential**	**a 0.59 (SE 0.08); p < 0.0001*** **b 2.33 (SE 0.74); p < 0.012***	**0.21,** df = 9	**1.24**
	Logistic	a 0.65 (SE 0.29); p = 0.05 b -1.95 (SE 5.56); p = 0.74 c 2.29 (SE 7.53); p = 0.77	0.25, df = 8	4.90

Note: Total and endemic fish recovery was characterized as rising immediately after a minimum distance threshold, as predicted consistently by the asymptotic exponential models. The chosen models are highlighted in bold. AIC = Akaike Information Criteria; *Statistical significance level alpha = 0.05

Discussion

The potential of undammed tributaries to mitigate river regulation impacts

These results suggest that recovery of freshwater fish species, including endemics from the WG, is still promising under the current level of hydrological regulation in the upper catchment of the Malaprabha river of the WG. Clearly, this result owes to the fact that undammed tributaries with adequate discharge (stream order 3) are still present in the basin, and appear to be mitigating the cumulative impacts of large and small barriers in the basin to some extent. Nearly all endemic species reappeared within a 5 km threshold distance downstream of barriers suggesting promising potential for recovery. Undammed tributaries might have high diversity of riverine habitats and serve as potential breeding grounds for fishes or as alternative migratory routes for potamodromous species (Sedell et al., 1990; King et al., 2009). It is likely that smaller barriers still offer partial or near-complete passage to fishes, especially during the monsoonal flooding pulse, as compared to the largest barrier in the study area. Our study highlights the contribution of undammed tributaries in replenishing catchment-scale functional connectivity across regulated stream networks (Johnson, 2002). This result is important for freshwater conservation planning to mitigate cumulative biodiversity impacts of river regulation in human-modified basins (Nunes et al., 2015).

Influences of local stream characteristics on species recovery

Previous studies from regulated temperate and tropical river systems have reported partial recovery in terms of fish community composition (Niemi et al., 1990; Storey et al., 1991; Detenbeck et al., 1992). Proximity to reference sites and distance from barriers (Davey and Kelly, 2007; Kubach et al., 2011) were identified as key determinants of species recovery, as in our study. Other than distance, the nature of dam operations, age of barriers, local habitat conditions and anthropogenic impacts could aid or limit recovery (Ellis and Jones, 2013; Stoll et al., 2014; Piller and Gehber, 2015). For instance, the recovery of some species might have been influenced because of sensitivity to local pollution sources, sand-gravel mining or fishing impacts (e.g. rheophilic carps such as *Tor khudree* and *Hypselobarbus dobsoni*). The loach *Paracanthocobitis mooreh*, which requires sand-gravel substrates for spawning showed low recovery. Specialized habitat preferences of torrent-dwelling fishes such as *Bhavania*, *Nemacheilus* (loaches) and *Glyptothorax* (catfish) can lower the chances for their recovery. These species might have been locally extirpated or declined in abundance in the basin following regulation (authors; field observations), owing to their limited swimming and dispersal ability to escape habitat alterations caused by flow regulation (Daniels, 2002; Raghavan et al., 2008). Importantly, these species are either highly localized endemics or are enlisted as threatened (Molur et al., 2011) and hence the critical threshold of regulation for their recovery might not be identified without analyzing relative abundance patterns. For instance, the endemic carp *Hypselobarbus dobsoni*, which was feared to have disappeared from its native range in the WG (M. Arunachalam, pers. comm.) was detected, but only 5 km below barriers. At the same time, the presence of localized deep pools can provide refuge for species during the dry-season and drought periods and allow recovery in spite of barriers (Sedell et al., 1990) In turn, regulation may have benefitted limnophilic and omnivorous species such as *Mystus* catfishes, as seen also in the Bhadra river (V. Atkore, unpublished data) Fish communities that showed high recovery were dominated by rheophilic, heterotrophic, and periodic-breeding species, with whom recovery levels showed no clear association. Interestingly, some benthic gravel-spawning catfishes, which we expected to be unaffected by regulation, showed low recovery.

For a more robust assessment of recovery for rare species, abundance data collected using methods to assess detectability and movement patterns, need to be incorporated in future assessments (Albanese et al., 2009). In addition, spatial variation in environmental factors (e.g. water quality) could have influenced recovery processes (Storey et al., 1991; Detenbeck et al., 1992). As noted in our results, dissolved oxygen increased and total alkalinity decreased with distance from barriers. Immediately downstream of barriers, groundwater contributions to stream flow would be higher, contributing to higher alkalinity, and at greater distances surface flows from undammed tributaries might restore surface- to groundwater ratios, lowering alkalinity. Unlike DO and alkalinity, the effects of water temperature and rocky habitat were independent of distance from barriers. Local human disturbances (fishing pressure, diversions for irrigation, water pollution, and substrate extraction) could have affected these variables and therefore are likely to affect species recovery irrespective of the influence of upstream barriers. Future detailed studies must attempt to understand how local anthropogenic disturbances and basin-scale flow alterations might affect recovery.

Simple metrics for rapid assessment of fish recovery in regulated river basins

I believe that defining a reference species composition representative of unregulated conditions helped us perform neat comparisons of upstream unaffected sites with downstream sites under the impact of regulation (Voelz and Ward, 1989; Kubach et al., 2011). Detecting species recovery is challenging, given that pre-dam information on fish community composition is limited, or lacking entirely. As a result, space-for-time assessments of river regulation impacts are the norm in most regions, despite their limitations in detecting temporal changes in compositional patterns in freshwater taxa (Detenbeck et al., 1992). Ideally, long-term studies would be robust in detecting impacts of hydrological barriers through nested and intensive sampling schemes, to understand processes of species recovery (Ryon, 2011; Ellis and Jones, 2013), subject to broader influences of climate variability and land-use changes (Dee Boersma et al., 2001; Kibler and Tullos, 2013). Future studies must also assess fish movements both upstream and downstream of barriers using mark-recapture framework (Albanese et al., 2003). Though this study is limited in scope to capture these dynamics, it provides simple and effective metrics of fish community recovery that may find application in rapid ecological assessments (Galatowitsch et al., 1998).

Implications for river restoration and conservation in tropical rivers

To maintain high recovery in dammed basins, my observations suggest that 5-10 undammed and undisturbed 2nd and 3rd order streams each need to be protected in the catchment of approximately 500 sq.km area. The observed recovery might indicate a tipping point beyond which irreversible losses (local extinctions) are likely if remaining tributaries are also slated for future regulation. Flows of these remnant streams are already being abstracted for intensive agriculture. These results indicate that strictly limiting any future regulation of these streams will be critical to sustain fish species recovery. Smaller barriers might have low impact on species recovery and their impacts in future water development plans need to be assessed case-by-case through detailed field-based ecological flow modelling exercises to identify thresholds needed for effective recovery. The recovery thresholds (2-5 km) that I report can be useful indicators of cumulative impacts on recovery perhaps applicable to other regulated river basins in the WG. Similar levels of regulation and protection were thought to enhance population persistence of endemic and threatened fish species in the regulated Muse and Dutch rivers (Leeuw et al., 2005).

A recent inter-basin transfer from the headwaters of the Mhadei to the east-flowing Malaprabha basin could potentially affect river habitats essential for specialized endemic fishes (Atkore et al., 2012). The canal plans to divert 7.5 thousand cubic meter (tmc) of water annually to two cities located downstream in Karnataka state for drinking water purpose. Recently, the Mhadei Water Dispute Tribunal in its interim order on 27th July 2016 rejected Karnataka's demand for water which led to escalated protests in many cities of Karnataka. These protests make it clear that human appropriation of river water is only going to increase in this basin, and adverse impacts on river fish diversity may be imminent with continued flow regulation. In this context, our results can inform policy-makers on how conservation of stream fishes and other riverine biodiversity could be achieved, despite intensifying demands, in future negotiations on water sharing and management in this basin.

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Chapter 6

Synthesis and Conclusion

Globally, freshwater ecosystems are severely threatened due to over-exploitation both for water and energy demands of society. As a result, freshwater fish – one of the important components of these ecosystems - have become highly vulnerable. Stream fish community ecology has been well studied both in the temperate and tropical regions. Typically, most studies conducted have evaluated the patterns of diversity, abundance and distribution which often interest stream ecologists. However, due to increasing threats to freshwater systems, extinction risk for riverine fishes is exceeding that of the natural rate of extinction (Dias et al., 2017). Studies that quantify fish-environment relationship are on the rise (Latin America, Mediterranean, Australia, and New Zealand) including Asian rivers (South and South East Asia).

Tropical Asian rivers systems harbor a wide array of habitats that support extraordinarily rich aquatic diversity (Dudgeon, 2000). India hosts more than 950 freshwater fish species in its diverse freshwater habitats (lakes, streams and rivers) (Jayaram, 2010). However, these freshwater habitats are being over exploited for various developmental projects and water diversion schemes.

The WG region, part of the Western Ghats–Sri Lanka Biodiversity hotspot - currently holds particularly high freshwater fish endemic diversity (66 %) compared to other freshwater taxa (Dahanukar & Raghavan, 2013; Raghavan et al., 2016). IUCN reports suggest that our knowledge of patterns of diversity and distribution of fish communities are still incomplete in this region (Molur et al., 2011). However, basin-wide approaches within a larger ecoregion which enable an understanding of the complete structure and organization of fish communities at multiple spatial scales ranging from local (segment) to regional (stream order) or basin level (catchment level), are lacking (Hauer and Lamberti, 2007). This can also help disentangle anthropogenic and environmental factors that drive species composition across scales. Thus data collected in a nested design within and across basins offer a consistent surveying methodology enabling both inter and intra river comparison in fish communities with regard to its stream environment (Macnaughton, 2016). Previous studies conducted in this region on fish communities have contributed to knowledge on fish-stream characteristics (stream order, habitat) and few fish guilds (Arunachalam, 2000; Bhat, 2004; Raghavan et al., 2008; Johnson and Arunachalam, 2010; Abraham and Kelkar, 2012; Chakrabarty and Homechaudhuri, 2013; Kundu et al., 2014) but did not include water chemistry, comprehensive fish guilds or assess the effect of anthropogenic or environmental factors on fish guilds. None of these studies have attempted to understand the possibility of species recovery especially below the dam in changing riverscapes.

The primary objective of my thesis was to understand the different drivers of fish diversity (richness, abundance) and composition within as well as across four river sub-basins and evaluate the possibility of species recovery below hydrological barriers. Overall, I recorded a total of 93 species belonging to nine orders and 18 families from 18,322 individuals. About 99% of the diversity was comprised of three orders – Cypriniformes, Siluriformes and Perciformes. Of the 93 species sampled, I found about 50 fish species were endemic to the WG region (Molur et al., 2011; Dahanukar and Raghavan, 2013). Some genera such as *Barilius* and *Barbodes* were restricted only to the relatively unregulated sub-basins (Bhadra and Tunga) while other genera such as *Sicyopterus* and *Mugil* were found only in regulated west-flowing Mhadei basin. Malaprabha had three genera exclusively to its basin. They include *Chela*, *Systomus* and *Schimatorhynchus*. The distribution of these genera in each of the basins suggest a biogeographical effect.

I attempted to understand factors (environmental and anthropological) that drive the native fish richness and abundance in 152 stream segments spread across four sub-basins. Several important insights emerge from this study that would potentially aid river conservation efforts both for the rivers in the WG's, and elsewhere in India: (1). Species diversity (richness and abundance) was higher in large rivers (Mhadei and Malaprabha) than in smaller rivers (Tunga and Bhadra); (2) River regulation impacted surface dwelling guilds while benefiting mid and bottom dwelling fish guilds; (3) Water chemistry variables such as dissolved oxygen, calcium hardness and alkalinity also influence diverse fish guilds indicating importance of water monitoring; (4) Non-regulated rivers harbor diverse stream substratum that in turn shape fish community composition; (5) fish species recovery can be achieved even in the regulated basins provided undammed tributaries are maintained below existing barriers.

In second chapter, I examined the drivers of species richness and abundance in four river sub-basins at multiple spatial scales. Information on site specific richness, abundance and species composition and habitat use of stream fish communities is vital for river conservation. My results based on data collected across 152 stream segments on environmental and fish diversity suggest that fish diversity (richness and abundance) was influenced by diverse set of stream characteristics as well as water chemistry. My results suggest that diverse fish species have a complex association with environment and water chemistry. Streams with high disturbance levels were associated with higher species richness while fish abundance was higher in less disturbed segments, indicating that generalist and disturbance tolerant species contributed to greater richness in the WG. However, WG endemic and generalist species also utilized less disturbed environments in the spawning period.

In terms of river basins, Malaprabha was the most speciose with 53 species, of the three sub-basins (Mhadei, Tunga and Bhadra). The presence of a reservoir downstream of the Malaprabha river facilitated fish movement upstream resulting in a higher observed species richness. Additionally, pool habitat modified by various impoundment structures (check dams, barrages) have created a niche space allowing many species to coexist. Mhadei was the second richest with 47 species and this could be due to the presence of a good network of perennial streams of 1^{st} and 2^{nd} orders apart from the habitat modification due to many river barriers (check dams), that again might lead to increased niches. Tunga sub-basin was the third sub-basin in species richness with 45 species. Species richness in Tunga was possibly due to the presence of perennial streams of 1^{st}, 2^{nd} and 3^{rd} stream orders that provide a gentle gradient in the sub-basin, which in turn yields a variety of river habitats (run, riffle and pool). Bhadra river was very similar to Tunga in terms of its habitat diversity and perennial stream network apart from also being connected to a reservoir downstream. However, it was relatively species poor with only 24 species compared to other sub-basins. A steep gradient within the basin due to natural waterfalls situated in the headwater region could have restricted fish movement. The habitat heterogeneity hypothesis suggests that more diverse habitats support higher species richness (Ricklefs and Dolph, 1993). However, this study suggests that the homogeneous habitats (pool) formed due to temporary impoundments as well as small check dams supported a higher species richness.

I also evaluated the conservation status of all the species sampled in the study area according to the current IUCN Red list (Molur et al., 2011). I found that 16 species identified in the study were not evaluated previously by IUCN. Additionally I described a new fish species called Kudremukh barb (*Pethia striata*) from Tunga sub-basin. These findings indicate that more systematic survey efforts are required to discover new fish species from the headwater regions (Atkore et al., 2015). I also report a healthy population of critically endangered species *Barbodes wynaadensis* within the Kudremukh National Park and a record of *Hypselobarbus thomassi* in the Malaprabha sub-basin. A new extension record of *Labeo dussumieri* from Bhadra river is reported from this study. Moreover, there is an urgent need to focus scientific and conservation attention on not just species but also their potential breeding habitats.

Species diversity (richness) measures alone do not reveal true community composition which is often important for conserving complex river systems in human dominated landscapes (McKnight, 2007). Human impacts in stream environment resulted either species gain (via introduction) or species loss (extinction) (Xu et al., 2015), and therefore, assessing the species composition or species turnover in relatively less disturbed river systems offer vital ecological insights as it further guide us prioritize crucial river segments for their protection. The Bhadra and Tunga sub-basins (relatively unregulated basins) were studied to determine species turnover (changes in species composition along a river gradient). Both of these rivers originate from the same geographical area (Gangamoola at 1160 m elevation in Kudremukh National Park) and share similar environmental features (rainfall, temperature, habitat and land use types). The species turnover or spatial structure of fish communities was studied at two scales, at local (segment) and at a sub-basin scales. Mantel's correlogram indicated a sine-hole pattern suggesting a high turnover at smaller spatial scale in both the sub-basin which also indicates dispersal limitation (Astorga et al., 2011; 2014). Mantel's r was also positively correlated with stream order, canopy cover, and negatively correlated with width to depth ratio and water temperature in Bhadra basin, while in Tunga, Mantel's r was positively correlated with substrate and negatively correlated with electrical conductivity. This strong influence of environmental variables on species turnover suggests that niche based processes may play an important role in structuring of these communities (Astorga et al., 2011; 2014).

These results clearly suggest that unregulated river segments especially situated in the headstream regions (within the national park boundary) offer habitat for species composition. A gentle elevation gradient maintain diverse habitat structure, facilitates fish mobility upstream-downstream environment, good water quality and species composition. Certain habitat specialist fish species only prefer relatively undisturbed environment to complete their life cycle (e.g. *Tor khudree*, *Barbodes wynaadensis*, *Balitora mysorensis* etc found in these basins) and any habitat alteration might severely affect their survival in the future.

Species richness and composition yield rich ecological knowledge on aquatic communities but, information on species guilds/ traits reveal functional aspect of community is often neglected from the Asian tropical river systems. To understand how hydrological barriers influence various fish guilds in two regulated and two non-regulated river sub-basin, I classified all sampled fish species that share similar geography (stream order, elevation etc) into different fish guilds based on primary data (intensive field data collection) as well as secondary data gathered from grey literature including theses, reports, books and published work (Lowe-McConnell, 1975; 1987; De Silva et al., 1979; Welcomme, 1985; Bhat, 2002; Johnson and Arunachalam, 2012; Chakrabarty and Homechaudhuri, 2013). Guild species composition varied between regulated and non-regulated sub-basin with more than half of the endemic species (including headwater habitat specialist) confined to non-regulated sub-basin. To determine, whether hydrological degradation was also due to excessive water abstraction, I analyzed data on disturbance regime as well as rainfall and river discharge data collected for the period 1979 to 2013 from the state irrigation departments of Goa and Karnataka. I performed time series analysis to understand the trend in rainfall and discharge over these years. The rainfall showed insignificant decline but discharge declined significantly.

Higher levels of calcium hardness and total dissolved solids indicated poor water quality. Responses to environmental variables differed across three guilds. Overall, calcium hardness was negatively and total dissolved solids was positively correlated with guild richness. Additionally, guilds richness was higher for two of three guilds in regulated sub-basin than in the non-regulated sub-basin. Of the three guilds, the surface dwelling guild was negatively affected by river barriers (blocking their movement) while mid and bottom dwelling guilds benefited, likely due to an impoundment effect (Aarts and Nienhuis, 2003; Kanno and Vokoun, 2010). Changing water chemistry and river barriers together affect water column based fish guilds in the WG region. Future studies need to incorporate data on guild abundance, and water abstraction across many comparable river sub-basins. The insights from these results suggest that often neglected data on functional guilds might be crucial in forming policy in re-designing hydrological barriers in tropical region or designing mitigation measures in regulated rivers.

So far, studies on fish communities have demonstrated the factors causing fish diversity at multiple spatial scales in different ecoregions (Matthews, 1998; Pusey et al., 1998; Bhat, 2003; Gido and Jackson, 2010; Arthington et al., 2014). Given that rivers are heavily appropriated worldwide for water and energy demands, very few studies have actually attempted to understand species recovery downstream of a dam. In a hydrologically modified river basin (such as Malaprabha), I evaluated the role of species recovery with distance downstream below the dam. I hypothesized that, species recovery will decrease immediately below the dam and increase with increasing distance from the dam due to the contribution of the undammed tributaries. I tested and validated this hypothesis, and my results show that total species similarity (proportion of species encountered in dammed river segments to undammed river segments) and endemic species similarity (recovery) was low immediately downstream of a dam but increased with increasing distance from the dam. Species recovery was higher within a distance of 2 km and it reduced beyond 5 km. The pattern was also similar in the case of endemic species recovery. This recovery below the dam was mainly attributed to the joining of undammed tributaries to the main river channel which not only provides a refuge, feeding and breeding ground for many fish species but also ameliorates river water quality due to instream flow (Ellis and Jones, 2013; Penczak et al., 2014; Espirito-Santo and Zuanon, 2016). Future studies must assess the fish movement from upstream to downstream of barriers using mark recapture frameworks (Albanese et al., 2003) and collect more data on fish abundance and associated life-history characteristics to understand the role of species recovery. Although, I found fairly good evidence of species recovery in a regulated sub-basins of the WG's, this recovery could be temporary, given that most of the undammed and undisturbed tributaries in the river basin are being exploited for agriculture as well as hydropower regulation in near future. If such interventions are continued, fish decline may continue in the downstream sections and leading to low species recovery.

Conservation implications

This study is the first of its kind focused on freshwater fish which involve rigorous field sampling across four sub-basins of the WG rivers. The study compares the combined influence of hydrological barriers, water chemistry, environmental factors on diverse fish guilds, and assess the species recovery below the dam. Given the dwindling nature of freshwater habitat in the country, results emerging from this study have a huge conservation science implications. Similar studies can be replicated in other parts of the country to answer key ecological questions that may highlight the ecological as well as conservation significance of last free-flowing rivers in India. It is necessary to monitor water quality variables along with fish diversity in both disturbed and non-disturbed rivers. Composition of fish guilds may serve as important ecological indicators to understand the health of river systems. Conservation prioritization should therefore identify continuous stream segments that harbors diverse habitats with good water quality. It is also important to maintain few free flowing river sections that allow free movement for river fishes to perform feeding and breeding movements.

Overall, we need to prioritize undammed tributaries for protection from local pollution and monitor water chemistry in local hotspots of endemic fish diversity. Data generated from this study has filled a current knowledge gap on distribution as well as on the population status of many threatened species.

River segments which are less modified and perennial in nature offer diverse habitat types and substrate composition which are essential for maintaining headwater specialists and overall species composition. Maintaining a good network of connected stream orders in a basin provides a healthy fish population as well as an opportunity to test the structure of stream fish communities. Species turnover seems to be driven mainly by stream substrate and elevation (600-800 m) at short spatial scales. It is important to prioritize this elevation range for maintaining species composition within protected areas.

Diversity of fish in terms of their morphology, behavior and reproductive strategies offer a unique opportunity to understand how functional guilds provide an intuitive understanding of fish communities (Mouillot et al., 2013) and therefore, studying functional traits/guilds is an exciting field of research in stream fish community ecology (Winemiller et al., 2010). Among the various guild types, guilds such as water-column based guilds seem to provide interesting insights in relation to environmental variables as well as hydrological barriers. Future long-term monitoring programs should incorporate guild level information. Although crucial information on life-history strategies and breeding biology of many Indian fishes are grossly lacking, the guild-level information that has been generated as part of this work will aid in ascertaining future conservation strategies for rivers in the WG's as well as other Indian rivers.

It is important to separate effects of hydrological barriers, water chemistry and environmental variables and assess how fish composition is influenced by each factor and in combination. It is also important to quantify trade-off between hydrological regulation and environmental variables in shaping fish community composition. This study provides useful insights on some of these aspects. Having long-term data on stream discharge is vital in order to draw meaningful insights into how fish communities are influenced in regulated and non-regulated river sections. Future studies are required to take into consideration a basin with a good stream network that provides both control as well as disturbed segments (dams and other anthropogenic disturbances such as water uptake, substrate mining, fishing etc). Based on precautionary principle invoked from the study, a basin with 500 sq. km area (based on the sub-basin area of Malaprabha river) should maintain at least five to ten undammed streams to test the idea of species recovery. Studies should also focus on other factors that are likely to influence species recovery i.e. longitudinal connectivity, diversity in stream habitats, good water quality, biological traits of fish species and distance from the barrier etc.

In summary, I find that at smaller scales (segment level), stream fish communities (richness and abundance) are structured primarily by water chemistry and at larger spatial scales by stream size. At small spatial scales, fish species composition is influenced by substrate heterogeneity and at sub-basin scale, by stream order (surrogate for elevation). Fish guild richness was influenced primarily by water chemistry, environmental and hydrological barriers. However, this study did not assess the relationship between other climatic factors on fish communities at the basin or WG scale. It would be useful to incorporate such knowledge on native fish communities of the WG in India. Results from my thesis may provide useful insights for river management as the fish metric developed in the study (fish-environment relationship and fish recovery) might help in assessing the health of a river system. Systematic and comprehensive methodology developed in the study may aid in the river monitoring efforts. Identifying and maintaining reference sites in a modified river basin might also be useful metric to compare and assess the state of river degradation. This thesis answers some of the methodological and fundamental questions with regard to fish community structure in both modified and unmodified basins. And finally, results generated from my thesis may serve as a useful guide for future studies that aim to investigate the relationship between fish diversity indices and long term water chemistry and environment data.

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Appendix 2.1

Appendix - Ia. Details of sampling locations and disturbance regimes in the four sub-basins.

River basin	Stream name	Site name	Stream order	N	E	Elevation (m)	Disturb. rank	Disturb level	Disturbance type
Bhadra	Bhadra	Kadambi joint	3	13.23	75.17	829	1	Low	
Bhadra	Bhadra	Bh7	3	13.23	75.17	860	1	Low	
Bhadra	Bhadra	Oldgrass point	3	13.21	75.18	854	1	Low	
Bhadra	Bhadra	Kurinjikal	3	13.21	75.19	830	1	Low	
Bhadra	Bhadra	Khasigadde	3	13.21	75.19	834	4	Low	
Bhadra	Bhadra	Bhagvati	4	13.20	75.20	825	8	Medium	checkdam
Bhadra	Bhadra	Pandarmakki road	4	13.20	75.20	824	3	Low	
Bhadra	Bhadra	Bh-kachige joint	4	13.21	75.23	778	1	Low	
Bhadra	Bhadra	Khagundi	5	13.21	75.24	761	2	Low	
Bhadra	Bhadra	KIOCL	5	13.21	75.25	770	1	Low	
Bhadra	Bhadra	Nagraj mane	5	13.21	75.25	760	1	Low	water extraction for Kudremukh town
Bhadra	Bhadra	Kudremukh bridge	5	13.21	75.25	755	2	Low	
Bhadra	Bhadra	Hosmakki joint	5	13.21	75.26	750	3	Low	
Bhadra	Biligal	Biligal1	4	13.21	75.22	775	3	Low	
Bhadra	Biligal	Biligal3	3	13.20	75.22	805	1	Low	
Bhadra	Biligal	Biligal5	3	13.20	75.22	816	1	Low	
Bhadra	Kachige	Kachige1	4	13.21	75.23	778	1	Low	
Bhadra	Kachige	Kachige3	4	13.20	75.23	785	1	Low	
Bhadra	Kachige	Kachige4	4	13.20	75.23	790	1	Low	
Bhadra	Kachige	Kachige5	4	13.19	75.23	806	1	Low	
Bhadra	Singsar	Singsar1	4	13.21	75.22	810	5	Medium	
Bhadra	Singsar	Singsar2	4	13.21	75.21	814	1	Low	
Bhadra	Singsar	Singsar3	4	13.22	75.21	928	1	Low	
Bhadra	Kunya	Kunya1	3	13.21	75.25	780	1	Low	
Bhadra	Kunya	Kunya2	3	13.21	75.24	782	1	Low	
Bhadra	Kunya	Kunya3	3	13.22	75.24	795	1	Low	
Bhadra	Kunya	Kunya4	3	13.22	75.24	824	1	Low	
Bhadra	Kunya	Kunya5	3	13.22	75.24	829	8	Medium	checkdam
Bhadra	Carman	Carman1	4	13.23	75.26	795	1	Low	water extraction for Kudremukh town
Bhadra	Carman	Carman2	4	13.24	75.26	810	1	Low	
Bhadra	Carman	Carman3	3	13.24	75.25	814	1	Low	
Bhadra	Carman	Carman4	3	13.24	75.25	898	1	Low	
Bhadra	Hosmakki	Hosmakki 1	1	13.21	75.26	910	1	Low	

River basin	Stream name	Site name	Stream order	N	E	Elevation (m)	Disturb. rank	Disturb level	Disturbance type
Bhadra	Hosmakki	Hosmakki 2	4	13.20	75.26	920	8	Medium	checkdam
Bhadra	Hosmakki	Hosmakki 3	4	13.20	75.26	930	1	Low	
Bhadra	Hosmakki	Hosmakki 4	3	13.21	75.28	767	1	Low	
Bhadra	Nelibedu	Nelibedu1	3	13.20	75.28	802	1	Low	
Bhadra	Nelibedu	Nelibedu3	3	13.20	75.28	809	8	Medium	checkdam
Bhadra	Nelibedu	Nelibedu5	3	13.20	75.28	861	4	Low	
Bhadra	Somvati	Somvati1	2	13.15	75.30	1053	1	Low	
Bhadra	Somvati	Somvati2	3	13.18	75.32	802	12	High	private hydropower plant
Tunga	Mudba	Mudba1	4	13.31	75.13	664	1	Low	
Tunga	Mudba	Mudba2	4	13.31	75.13	670	1	Low	
Tunga	Mudba	Mudba4	4	13.31	75.12	675	1	Low	
Tunga	Mudba	Mudba5	3	13.31	75.12	700	1	Low	
Tunga	Mudba	Mudba8	2	13.30	75.13	700	5	Medium	
Tunga	Mundsar	Mundsar1	4	13.32	75.13	652	1	Low	
Tunga	Mundsar	Mundsar2	4	13.32	75.12	667	1	Low	
Tunga	Mundsar	Mundsar4	4	13.33	75.11	675	5	Medium	1waterpump
Tunga	Mundsar	Mundsar8	4	13.32	75.12	700	1	Low	
Tunga	Turad	Turad1	4	13.30	75.15	642	1	Low	
Tunga	Turad	Turad2	4	13.30	75.16	689	1	Low	
Tunga	Turad	Turad3	4	13.31	75.16	690	5	Medium	
Tunga	Turad	Turad4	4	13.31	75.16	754	1	Low	
Tunga	Karuchar	Karuchar1	4	13.33	75.14	667	5	Medium	1waterpump
Tunga	Karuchar	Karuchar2	4	13.33	75.13	672	5	Medium	
Tunga	Karuchar	Karuchar3	4	13.33	75.13	686	2	Low	
Tunga	Karuchar	Karuchar4	4	13.34	75.13	691	1	Low	
Tunga	Karuchar	Karuchar5	4	13.34	75.13	693	5	Medium	1waterpump
Tunga	Karuchar	Karuchar6	4	13.34	75.18	697	5	Medium	
Tunga	Korkan	Korkan1	4	13.34	75.17	656	5	Medium	
Tunga	Korkan	Korkan2	4	13.34	75.17	661	5	Medium	1waterpump
Tunga	Korkan	Korkan3	4	13.34	75.17	675	1	Low	
Tunga	Korkan	Korkan4	4	13.34	75.18	676	1	Low	
Tunga	Korkan	Korkan6	4	13.34	75.18	679	1	Low	
Tunga	Korkan	Korkan11	4	13.33	75.18	880	5	Medium	

River basin	Stream name	Site name	Stream order	N	E	Elevation (m)	Disturb. rank	Disturb level	Disturbance type
Tunga	Gangehole	Ghole2	3	13.27	75.16	776	1	Low	
Tunga	Gangehole	Ghole4	4	13.28	75.16	773	1	Low	
Tunga	Gangehole	Ghole6	4	13.29	75.16	716	1	Low	
Tunga	Gangehole	Ghole8	3	13.29	75.16	698	5	Medium	1waterpump
Tunga	Muje	Muje3	3	13.36	75.16	662	5	Medium	1waterpump
Tunga	Muje	Muje4	3	13.36	75.16	667	5	Medium	
Tunga	Muje	Muje7	4	13.36	75.16	680	5	Medium	
Tunga	Tanikod	Tanikod2	2	13.36	75.20	736	5	Medium	
Tunga	Tanikod	Tanikod4	2	13.35	75.20	811	1	Low	
Tunga	Vimala	Mudba-mundsar joint	4	13.32	75.13	761	2	Low	
Tunga	Vimala	Tn2	5	13.32	75.13	681	2	Low	
Tunga	Vimala	Acharmakk	5	13.32	75.14	677	5	Medium	
Tunga	Vimala	Tumbahalla	5	13.32	75.13	673	5	Medium	
Tunga	Vimala	Before Acharmakki	5	13.33	75.13	670	5	Medium	
Tunga	Vimala	Keshav mane	5	13.33	75.14	667	5	Medium	
Tunga	Vimala	Before Kerekatte1	5	13.33	75.14	665	5	Medium	
Tunga	Vimala	Before Kerekatte2	5	13.33	75.14	665	5	Medium	
Tunga	Tunga	Kerekatte	5	13.33	75.14	656	10	High	
Tunga	Tunga	Kerekatte school	5	13.33	75.14	655	6	Medium	washing & bathing
Tunga	Tunga	Trogen point	5	13.33	75.15	650	5	Medium	
Tunga	Tunga	Before Anand mane	5	13.34	75.16	650	2	Low	
Tunga	unga	Anand mane	5	13.34	75.16	650	5	Medium	1waterpump
Tunga	Tunga	Yadgar	5	13.34	75.17	650	1	Low	
Tunga	Tunga	Muje joint	6	13.35	75.17	645	5	Medium	1waterpump
Tunga	Tunga	Tanikod joint	6	13.36	75.20	645	1	Low	
Tunga	Tunga	Toursit point	6	13.36	75.21	635	6	Medium	1 waterpump
Tunga	Tunga	Salmara	6	13.37	75.21	630	5	Medium	1 waterpump
Tunga	Tunga	Nemmar	6	13.38	75.21	630	11	High	1waterpump
Malaprabha	Malaprabha	Amta	3	15.71	74.30	720	5	Medium	2 waterpump
Malaprabha	Malaprabha	Torali	3	15.71	74.32	715	5	Medium	1 waterpump

River basin	Stream name	Site name	Stream order	N	E	Elevation (m)	Disturb. rank	Disturb level	Disturbance type
Malaprabha	Malaprabha	Devachihatti	3	15.71	74.34	720	7	Medium	1 waterpump, riverbed completely dry during May 2014
Malaprabha	Malaprabha	Habbanhatti	3	15.72	74.36	714	6	Medium	barrage
Malaprabha	Malaprabha	Kusmali	3	15.71	74.38	700	7	Medium	
Malaprabha	Malaprabha	Malavi	3	15.66	74.43	711	5	Medium	
Malaprabha	Malaprabha	Olmani	3	15.71	74.41	693	12	High	1waterpump, dynamiting
Malaprabha	Malaprabha	Shankerpeti	4	15.68	74.42	653	7	Medium	washing & bathing
Malaprabha	Malaprabha	Asoga	4	15.63	74.48	643	10	High	sand mining, waterpump,fishing
Malaprabha	Malaprabha	Shedegali	4	15.62	74.50	650	7	Medium	washing & bathing
Malaprabha	Malaprabha	Rumewadi	5	15.63	74.52	655	9	High	sand mining, waterpump,fishing, pollution
Malaprabha	Malaprabha	Kupatgiri	5	15.64	74.53	650	9	High	fishing, waterpump, pollution
Malaprabha	Mangetri nala	Katgali	4	15.72	74.47	713	5	Medium	1 waterpump
Malaprabha	Mangetri nala	Valmiki	4	15.71	74.46	700	1	Low	
Malaprabha	Haltar nala	Shiroli	4	15.55	74.43	672	7	Medium	washing & bathing
Mhadei	Mhadei	Degaon	3	15.54	74.35	685	1	Low	
Mhadei	Mhadei	Before Kongla	5	15.59	74.38	635	1	Low	
Mhadei	Bhandura	Kongla	4	15.61	74.39	627	5	Medium	
Mhadei	Kotni nadi	Kotni	4	15.62	74.35	610	1	Low	
Mhadei	Mhadei	Below Kishnapur	6	15.56	74.22	48	1	Low	
Mhadei	Mhadei	Ustem	6	15.56	74.21	44	5	Medium	barrage
Mhadei	Mhadei	Ustem 2	6	15.56	74.21	44	8	Medium	
Mhadei	Mhadei	Sonal	6	15.54	74.20	41	10	High	sand-boulder mining
Mhadei	Mhadei	Cudcem	6	15.53	74.17	31	10	High	sand-boulder mining
Mhadei	Mhadei	Velgeum	6	15.52	74.16	27	7	Medium	barrage
Mhadei	Mhadei	Khadaki	6	15.50	74.14	18	8	Medium	barrage
Mhadei	Mhadei	Khotode	6	15.49	74.13	14	7	Medium	
Mhadei	Mhadei	Waghurme	7	15.47	74.03	14	12	High	bauxite mining
Mhadei	Mhadei	Jamgaon	4	15.56	74.39	673	5	Medium	
Mhadei	Bhandura	Nerse	4	15.60	74.41	650	1	Low	
Mhadei	Panshet nala	Talewadi	3	15.55	74.32	760	1	Low	

River basin	Stream name	Site name	Stream order	N	E	Elevation (m)	Disturb. rank	Disturb level	Disturbance type
Mhadei	Bail nadi	Bail nadi	3	15.64	74.28	721	9	High	illegal fishing by locals
Mhadei	Kalasa	Satrem	3	15.62	74.22	112	5	Medium	Polluted water
Mhadei	Kalasa	Derodem	4	15.60	74.22	84	5	Medium	
Mhadei	Kalasa	Nanodem	4	15.58	74.21	62	5	Medium	waterpump house by Goa Irrigation dept
Mhadei	Kalasa	Kankumbi	3	15.69	74.21	750	9	High	illegal fishing
Mhadei	Kalasa	Delta hotel	3	15.68	74.19	694	7	Medium	water extraction for hotel
Mhadei	Kalasa	Checkpost	3	15.68	74.18	733	1	Low	
Mhadei	Kotryachi nadi	Thane	5	15.61	74.15	85	5	Medium	fishing
Mhadei	Kotryachi nadi	Hedode	5	15.57	74.14	79	5	Medium	
Mhadei	Kotryachi nadi	Naneli	5	15.58	74.14	65	8	Medium	barrage
Mhadei	Kotryachi nadi	Velus	5	15.55	74.14	49	9	High	barrage
Mhadei	Patwal	Patwal	4	15.49	74.15	12	5	Medium	
Mhadei	Ragada	Vasant bandhara	1	15.40	74.26	135	8	Medium	checkdam
Mhadei	Ragada	Jambolim	4	15.39	74.22	21	5	Medium	
Mhadei	Ragada	Satpali	4	15.40	74.21	61	7	Medium	vehicle washing
Mhadei	Ragada	Panas	4	15.41	74.18	32	7	Medium	waterpump for oilpalm
Mhadei	Ragada	Shivade	4	15.42	74.14	16	5	Medium	
Mhadei	Ragada	Murmune	5	15.47	74.12	13	5	Medium	
Mhadei	Dudhsagar	Dudhsagar fall	4	15.31	74.31	146	3	Low	washing & bathing
Mhadei	Dudhsagar	Devachi kon	4	15.33	74.28	97	1	Low	
Mhadei	Dudhsagar	Dudhsagar juntion.	4	15.34	74.26	85	3	Low	tourist vehicles frequently passt hrough
Mhadei	Dudhsagar	Cullem	5	15.34	74.25	74	7	Medium	vehicle washing, bathing, water extraction for hotels
Mhadei	Dudhsagar	Shigaon	5	15.34	74.21	58	5	Medium	
Mhadei	Dudhsagar	Dabal	5	15.36	74.13	22	5	Medium	
Mhadei	Caranzhol	Cumtol 1	3	15.50	74.22	104	1	Low	
Mhadei	Caranzhol	Cumtol 2	4	15.52	74.20	50	7	Medium	washing clothes, cashew liquer plant
Mhadei	Karanjhol	Karanjhol	4	15.35	74.28	83	1	Low	

Appendix 1b. Systematic list of freshwater fishes found in the study area.

Orders	Family	Species	English names	Abundance	IUCN
Osteolossiformes	Notopteridae	*Notopterus notopterus*	Bronze featherback	2	LC
Cypriniformes	Cyprinidae	*Barilius bakeri*	Malabar baril	995	LC
		Barilius barna	Barna baril	1	LC
		Barilius canarensis	Jerdon’s baril	291	EN B1 abiii +2abiii
		Barilius bendelisis	Hamilton’s baril	30	LC
		Bariliius spp	-	4	NE
		Barbodes wynaadensis	Wayanaad mahseer	184	CR A2ace
		Cirrihinus fulungee	Deccan white carp	432	LC
		Cirrhinus spp	-	3	NE
		Chela cachius	Silver hatchet chela	1	LC
		Dawkinsia arulius	Aruli barb	171	EN B2abiii
		Dawkinsia filamentosa	Filament barb	453	LC
		Devario spp	-	5	NE
		Devario malabaricus	Giant danio	3494	LC
		Garra bicornuta	Tunga garra	185	NT
		Garra mullya	Mullya garra	3013	LC
		Garra stenorhynchus	Nilgiri garra	24	LC
		Haludaria melanampyx	Melon barb	55	DD
		Hypselobarbus curmuca	Curmuca barb	204	EN A2acd
		Hypselobarbus dobsoni	Krishna carp	56	DD
		Hypselobarbus dubius	Nilgiri barb	1	EN B2abiii
		Hypselobarbus jerdoni	Jerdon’s carp	234	LC
		Hypselobarbus thomassi	Red canarese barb	1	CR B2ab iii
		Labeo fimbriatus	Fringed-lipped peninsula carp	17	LC
		Labeo porcellus	Bombay labeo	2	LC
		Labeo spp	-	6	NE
		Oreichthys cosuatis	Kosuati barb	2	LC
		Osteochilichthys nashii	Nash's barb	828	LC
		Osteochilichthys thomassi	Konti barb	13	LC
		Pethia narayani	Narayan barb	381	LC
		Pethia sp	-	1	NE
		Pethia punctata	Dotted sawfin barb	2	LC
		Pethia setnai	Indego barb	205	VU B2 abiii
		Pethia striata	Kudremukh barb	24	NE
		Pethia ticto	Ticto barb	16	LC
		Puntius amphibius	Scarlet-banded barb	480	DD
		Puntius chola	Chola barb	4	LC
		Puntius dorsalis	Long snouted barb	5	LC
		Puntius sahyadriensis	Khavli barb	441	LC
		Puntius sophore	Spotfin swamp barb	21	LC
		Rohtee ogilbii	Vatani rohtee	8	LC

Orders	Family	Species	English names	Abundance	IUCN
		Rasbora daniconius	Slender rasbora	1161	LC
		Rasbora labiosa	Slender rasbora	12	LC
		Salmophasia bacaila	Large razor belly minnow	67	LC
		Salmophasia boopis	Boopis razer belly minnow	3182	LC
		Salmophasia novacula	Novacula razor belly minnow	93	LC
		Schismatorhynchos nukta	Nukta	1	EN A2acd +3acd
		Systomus sarana sarana	Olive barb	64	LC
		Systomus sarana subnastus	-	27	NE
		Tor khudree	Deccan mahseer	119	EN B2acde
	Balitoridae	*Paracanthocobitius mooreh*	Cobitis mooreh	33	NE
		Bhavania australis	Western ghat loach	19	LC
		Balitora mysorensis	Slender stone loach	1	VU B2ab iii
		Nemacheilus denisoni	-	24	LC
		Nemacheilus spp	-	24	NE
		Mesonemacheilus spp	-	1	NE
		Nemacheilus triangularis	Zodiac loach	4	LC
		Nemacheilus rueppelli	Mongoose loach	5	LC
		Nemacheilus semiarmatus	Dotted loach	3	LC
		Lepidocephalus thermalis	Common spiny loach	31	LC
	Cobitidae	*Botia striata*	Zebra loach	10	EN B2 abiii
Siluriformes	Bagridae	*Batasio sharavatiensis*	Sharavati batasio	8	EN B1abiii +2abiii
		Mystus armatus	Kerala mystus	11	LC
		Mystus bleekeri	Day’s mystus	101	LC
		Mystus cavacius	Gangetic mystus	90	LC
		Mystus gulio	Long whiskered catfish	202	LC
		Mystus keletius	Yellow catfish	67	LC
	Siluridae	*Ompok bimaculatus*	Butter catfish	8	NT
		Ompok malabaricus	Goan catfish	15	LC
	Schilibidae	*Eutropiichthys spp*	-	1	NE
	Sisoridae	*Glyptothorax spp2*	-	1	NE
		Glyptothorax spp3	-	1	NE
		Glyptothorax spp4	-	1	NE
	Claridae	*Clarias batrachus*	Walking catfish	1	LC
Mugiliformes	Mugilidae	*Migul spp*	-	9	NE
Beloniformes	Belonidae	*Xenentodon cancila*	Freshwater garfish	93	LC
Cyprinodontiformes	Aplocheilidae	*Aplocheilus lineatus*	The striped panchax	59	LC
Synbranchiformes	Mastacemelidae	*Mastacemeblus armatus*	Spiny eel	1	LC
Perciformes	Ambassidae	*Chanda nama*	Elongated glass perchlet	112	LC
		Parambassis ranga	Indian glassy fish	63	LC
		Parambassis thomassi	Western ghat glassy perchlet	17	LC
	Cichlidae	*Etroplus maculatus*	Orange chromid	21	LC

Orders	Family	Species	English names	Abundance	IUCN
		Etroplus suratensis	Green chromid	155	LC
	Gobidae	*Glossogobius giuris*	Bareye goby	33	LC
		Glossogobius spp	-	6	NE
		Sicyopterus griseus	Clown goby	24	LC
	Channidae	*Channa gachua*	Dwarf snakehead	4	LC
		Channa micropeltes	Giant snakehead	1	LC
		Channa marulius	Murrel	2	LC
		Channa punctata	Snakehead	1	LC
		Channa striata	Snakehead murrel	25	LC
Tetraodontiformes	Tetraodontidae	*Carinotetradon travancoricus*	Dwarf pufferfish	11	VU
		Arothron leopardus	Banded leopardblowfish	2	DD

Note: LC – Least concern, NE – Not evaluated, DD-data deficient, EN-Endangered, CR- Critically endangered, VU – Vulnerable, NT- Near thrtn.

Appendix – 2.2: .Range (minimum, maximum), mean and standard deviation of environmental variables.

Variable	Unit	Min	Max	Mean	SD
Total alkalinity	Mg/l	11	125.5	48.60	23.98
Free.co2	Mg/l	0.46	81.73	41.75	25.09
Chloride	Mg/l	8.52	284	26.08	29.20
Calcium hardness	Mg/l	3.69	426.72	50.52	86.69
Total hardness	Mg/l	7.3	904	68.76	124.6
Inorganic nitrates	Mg/l	0.01	1.45	0.25	0.22
Inorganic phosphates	Mg/l	0.001	0.77	0.14	0.12
Dissolved oxygen	Mg/l	4.55	16.62	8.90	2.10
Velocity	m3/s	0.029	1.3	0.23	0.22
Discharge	m3/s	0	0.019	0.006	0.006
Depth- width ratio	-	0.005	0.16	0.040	0.027
Water temperature	^{0}C	16	34.2	23.21	3.90
pH	-	5.6	18.6	7.42	1.31
Electrical conductivity	µm/s	0	0.16	0.03	0.03
Total dissolved solids	ppt	0	0.12	0.027	0.026
Canopy cover	%	0	95	49.10	25.50
Rocks	%	0	60	11.20	15.92
Boulders	%	0	80	11.19	12.11
Cobbles	%	0	50	16.08	11.46
Pebbles	%	0	50	18.43	12.38
Gravels	%	0	80	28.42	17.05
Sand	%	0	60	11.50	10.67
Leaves & woods	%	0	90	3.99	9.33

Appendix – 2.3. Exploratory plots

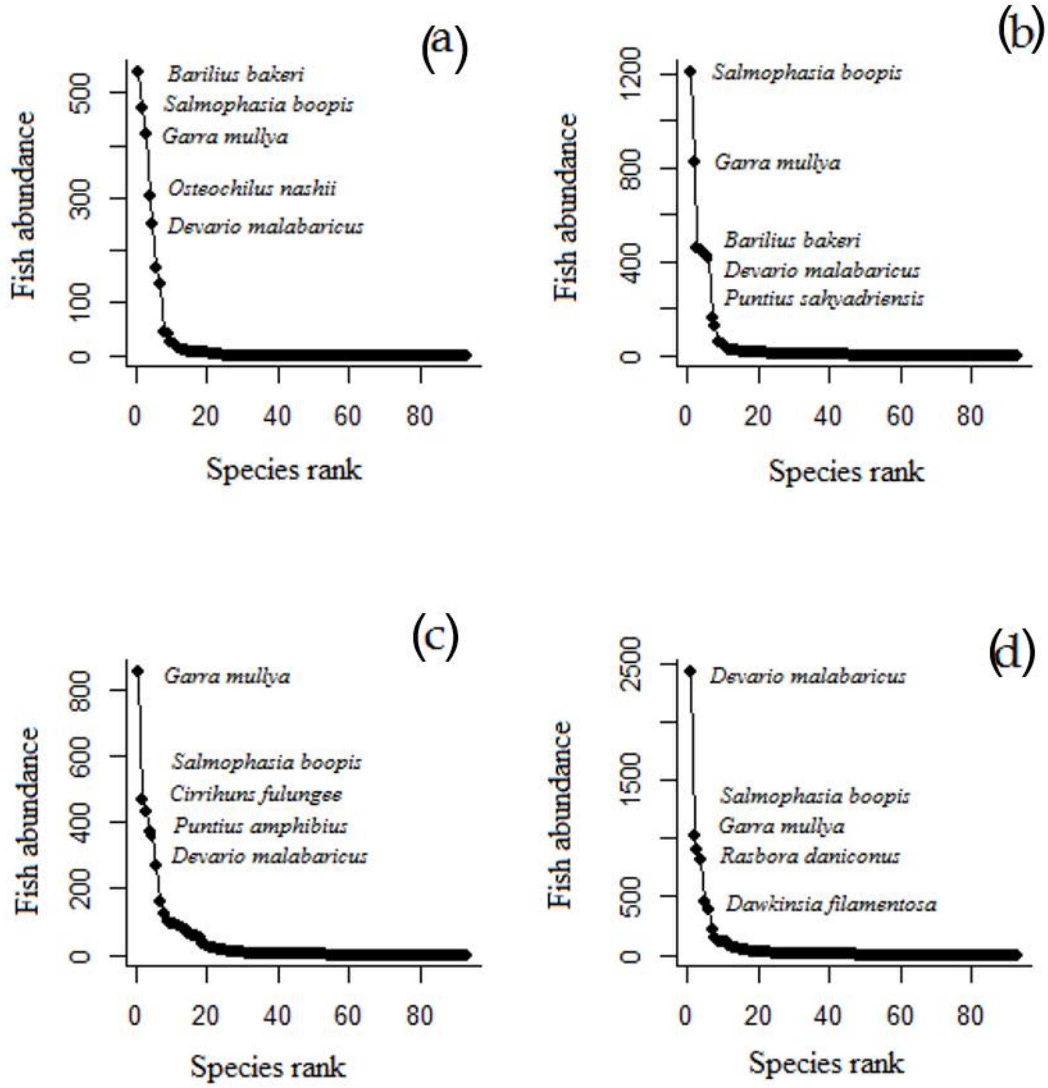


Figure i). Rank abundance of fish species in four river sub-basins (a) Bhadra, (b) Tunga, (c) Malaprabha, (d) Mhadei.

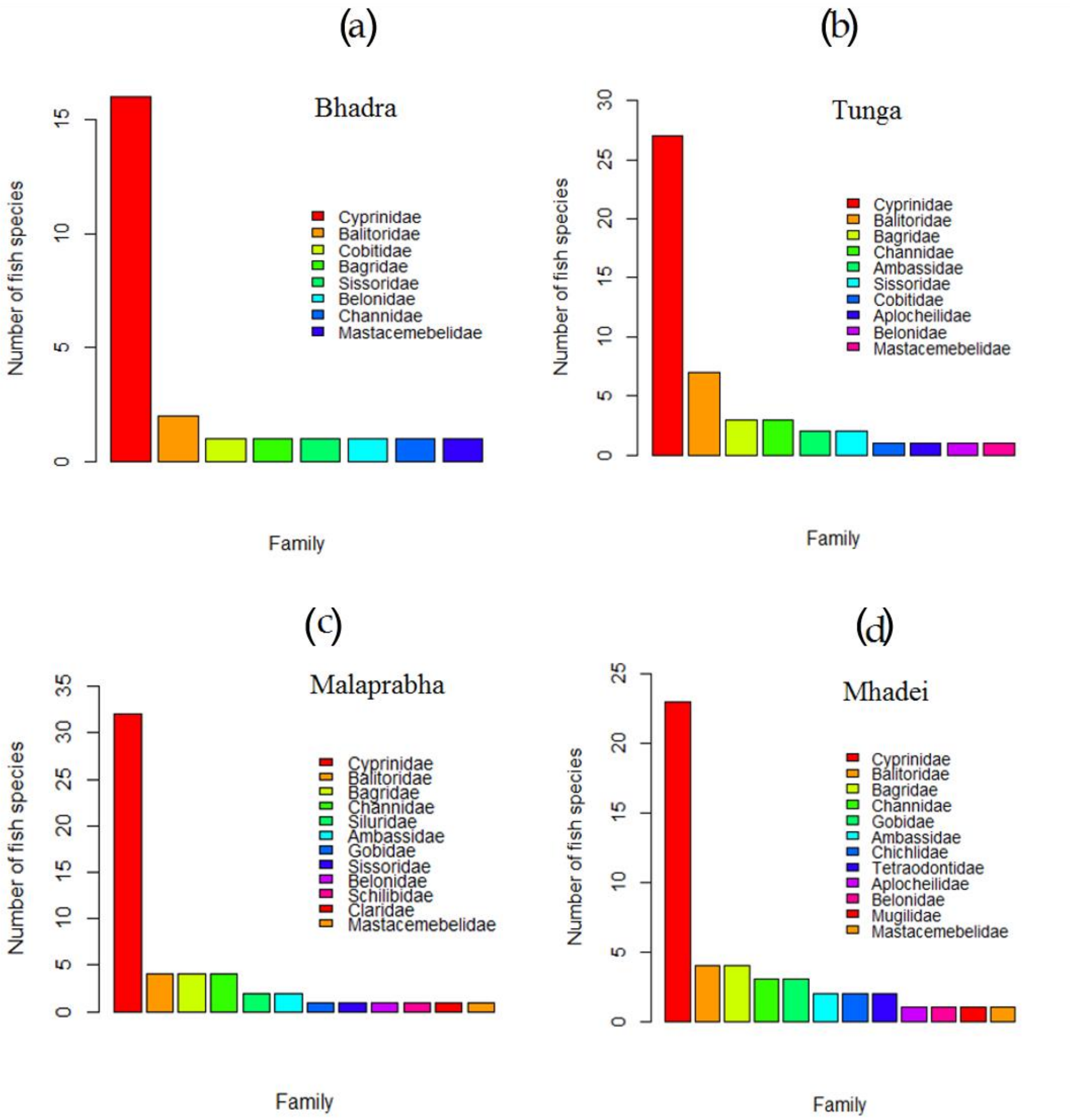


Figure ii). Dominant fish families in each river sub-basin respectively. (a) Bhadra (b) Tunga (c) Malaprabha (d) Mhadei.

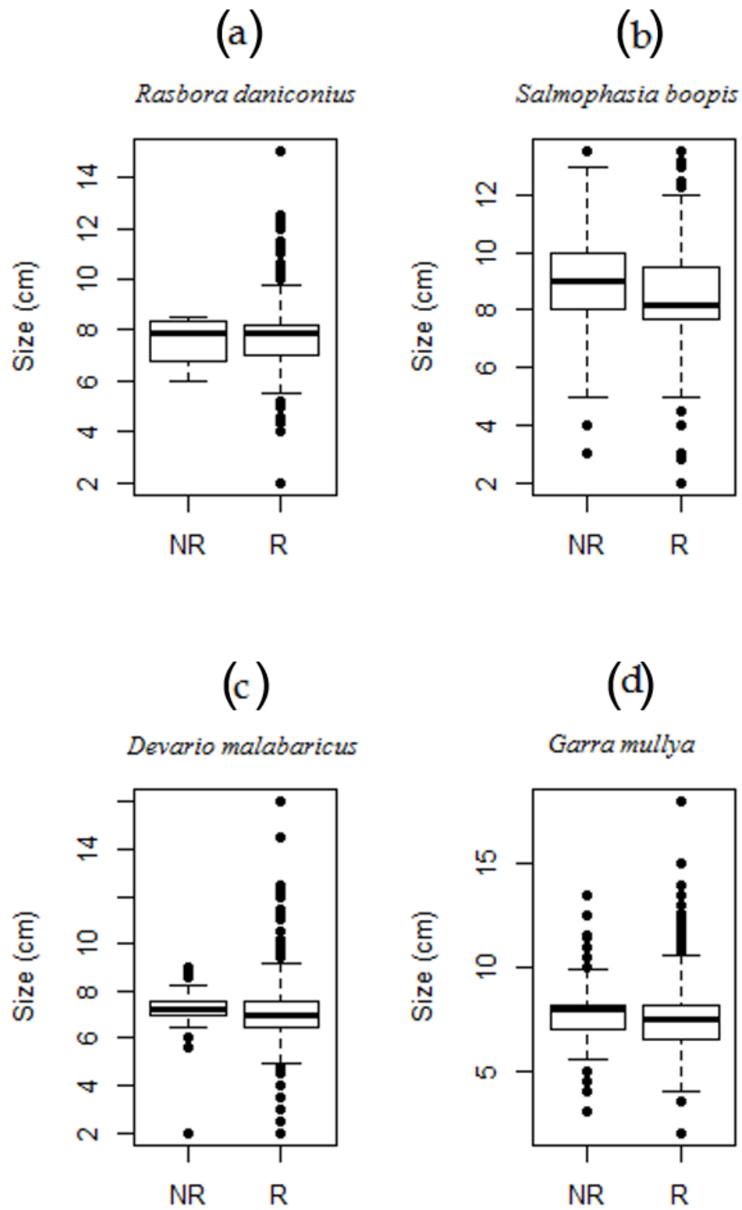


Figure iii). Size class for four dominant fish species in regulated and non-regulated basins. (a) *Rasbora daniconius* (b) *Salmophasia boopis* (c) *Devario malabaricus* (d) *Garra mullya.*

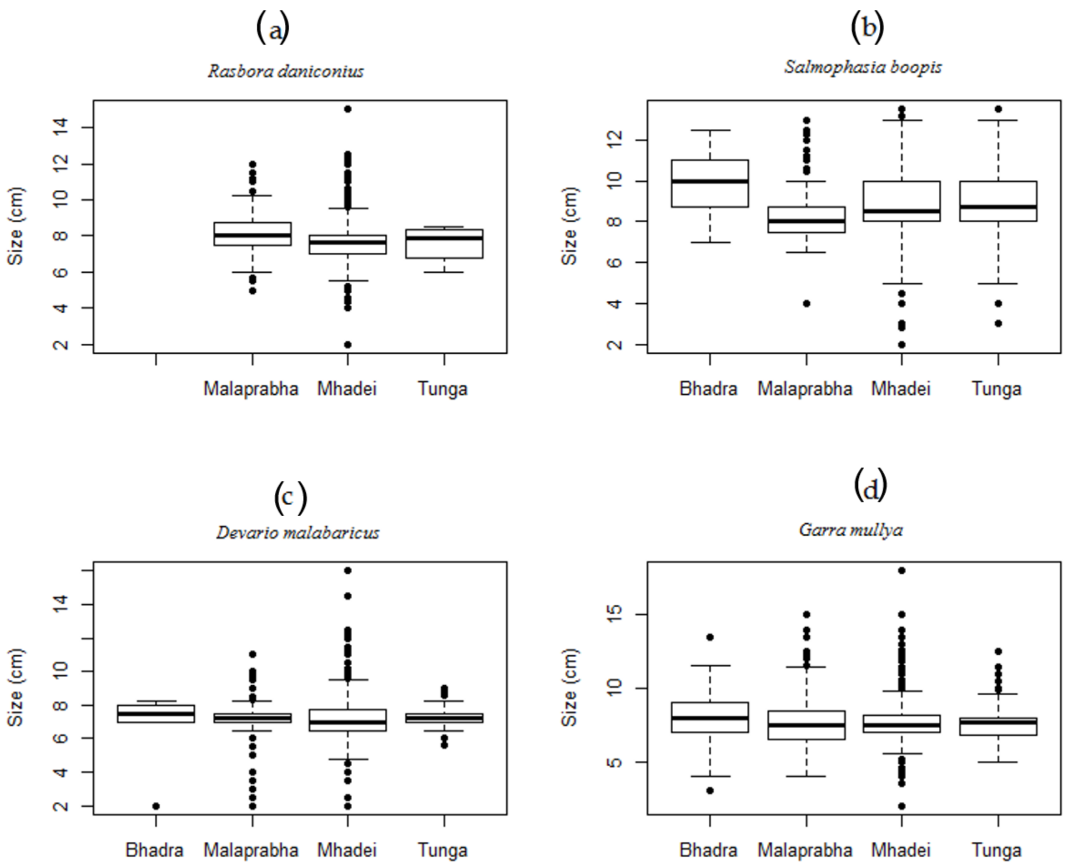


Figure iv). Size class for four dominant fish species in studied river sub-basins.(a) *Rasbora daniconius* (b) *Salmophasia boopis* (c) *Devario malabaricus* (d) *Garra mullya.*

(a)

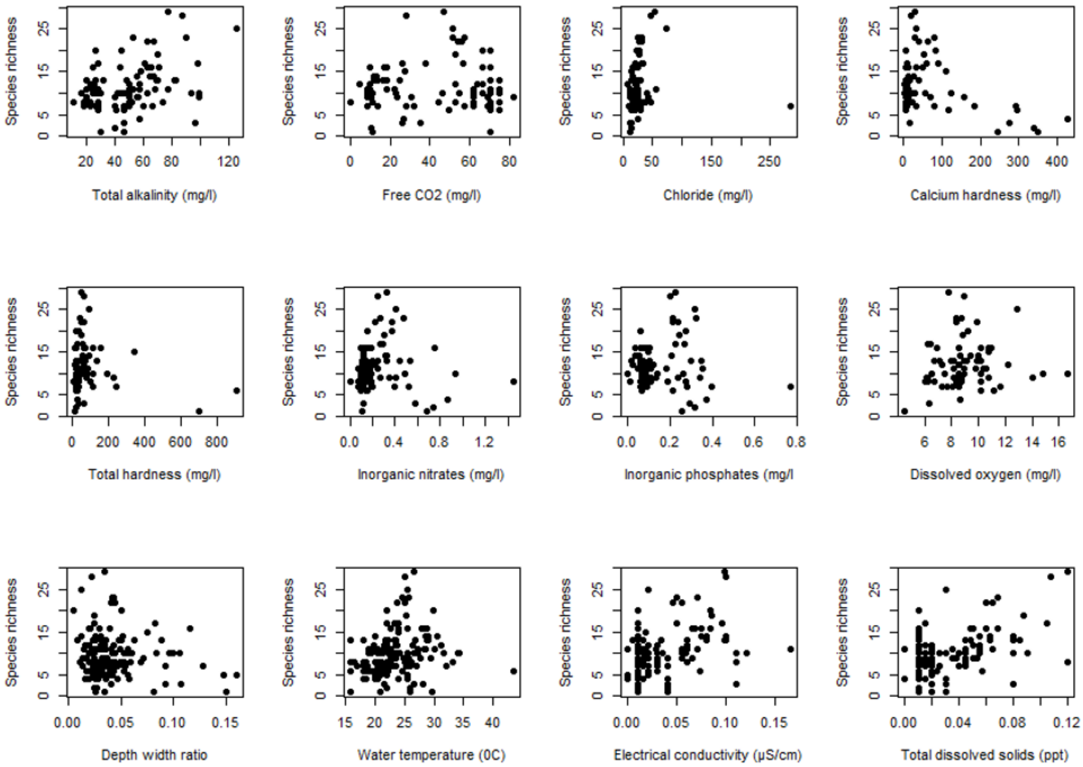


Figure v). (a) Relationship between species richness and habitat covariates.

(b)

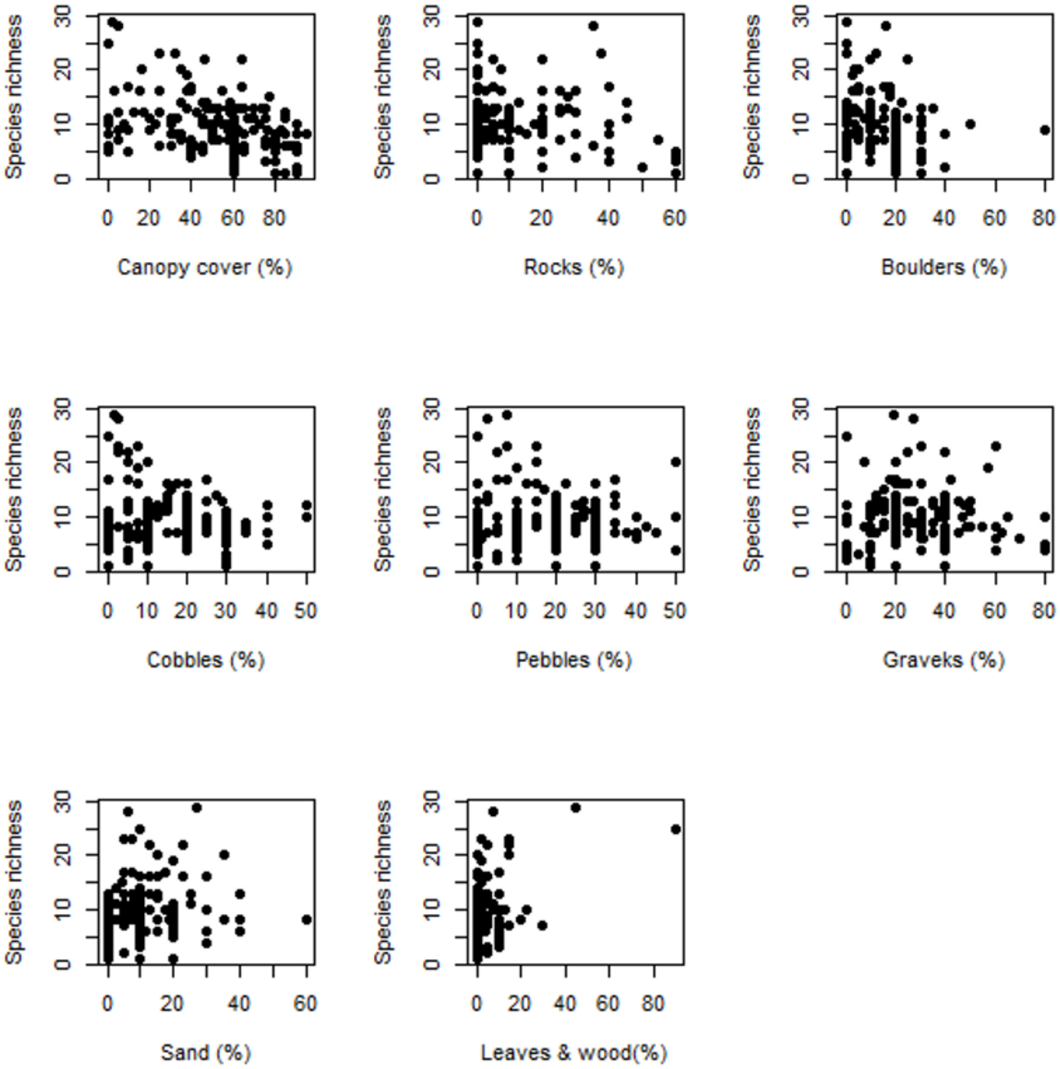


Figure vi). (b) Relationship between species richness and habitat covariates.

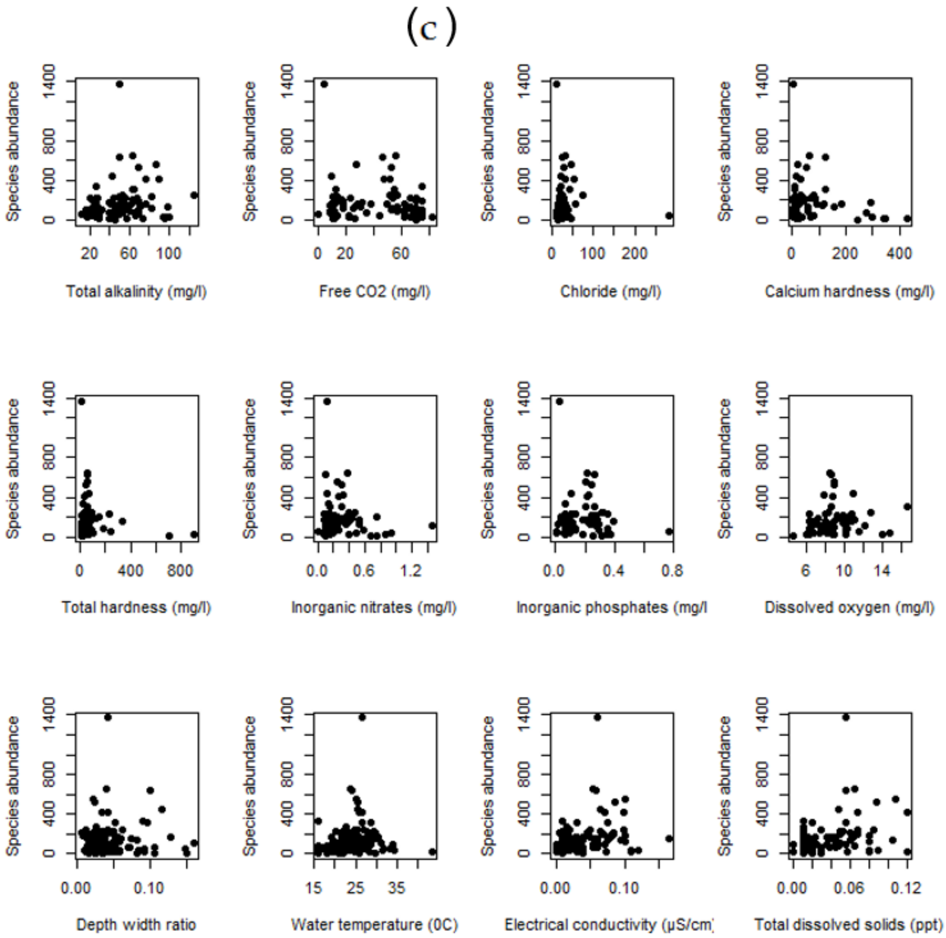


Figure vii). (c) Relationship between species abundance and habitat covariates.

(d)

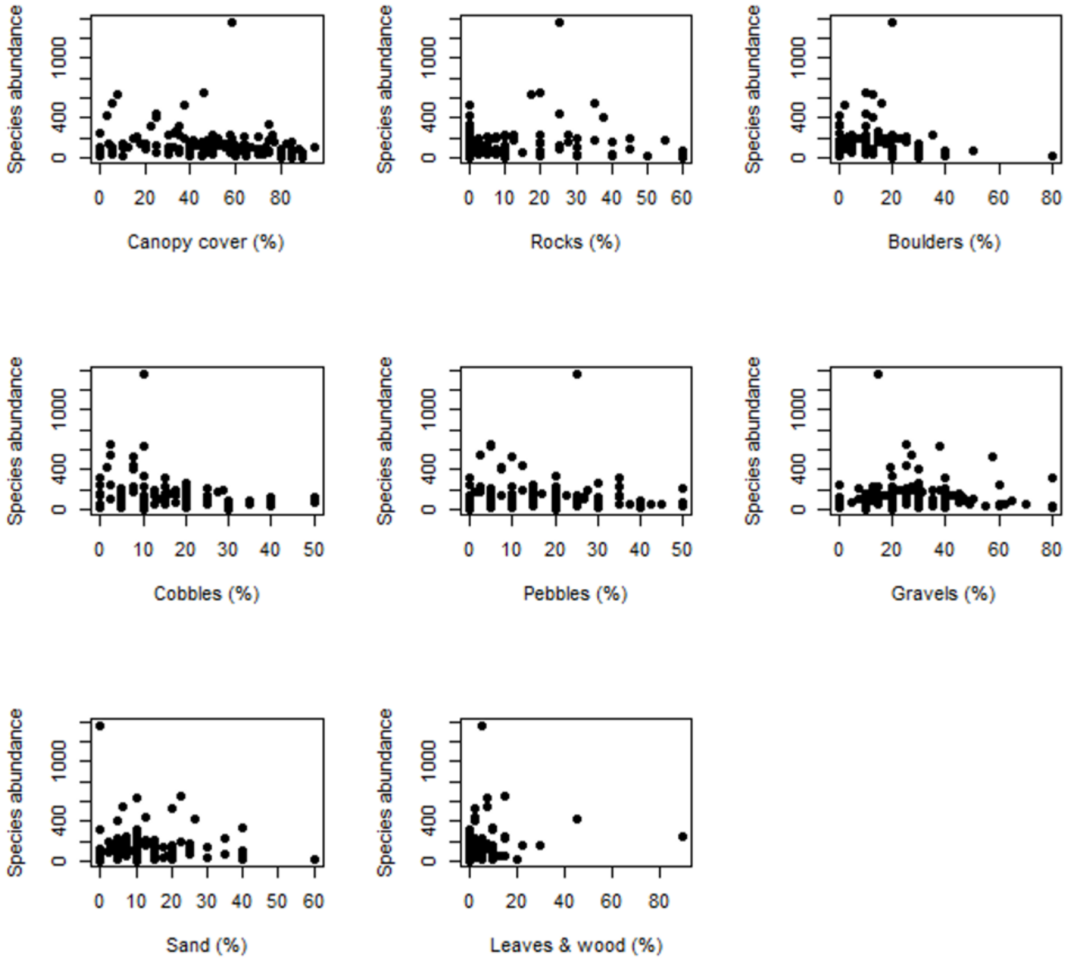


Figure viii). (d) Relationship between species abundance and habitat covariates.

Appendix – 2.4

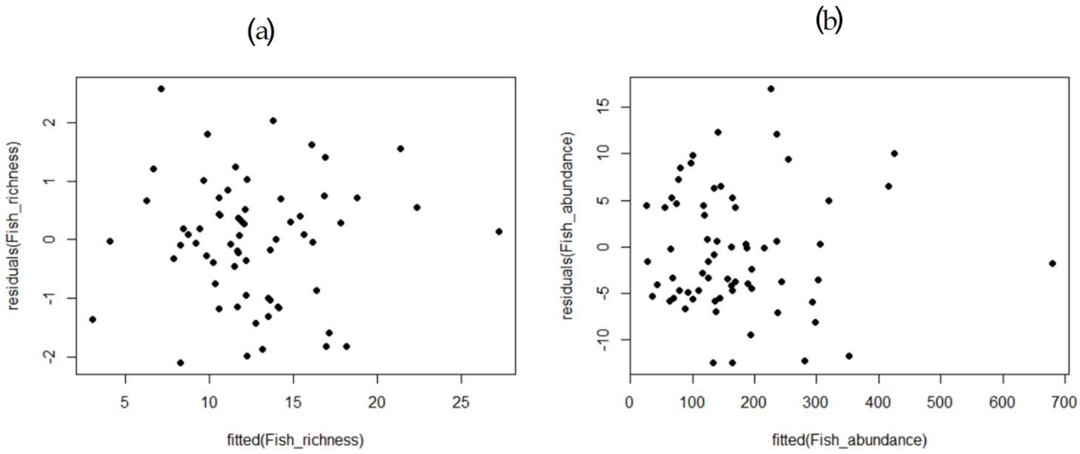


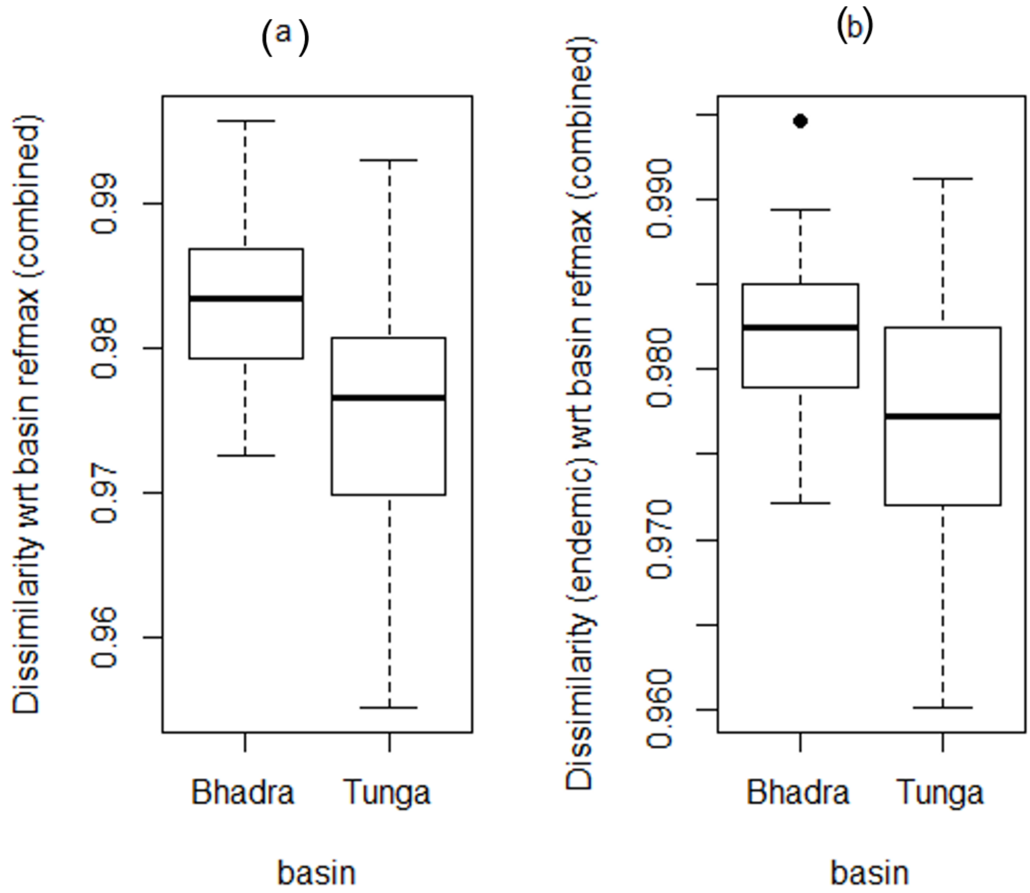
Figure ix). The diagnostic plots for generalized linear model for fish richness and fish abundance (a) residual fish richness vs fitted fish richness (b) residual fish abundance vs fitted fish abundance

Appendix 3.1

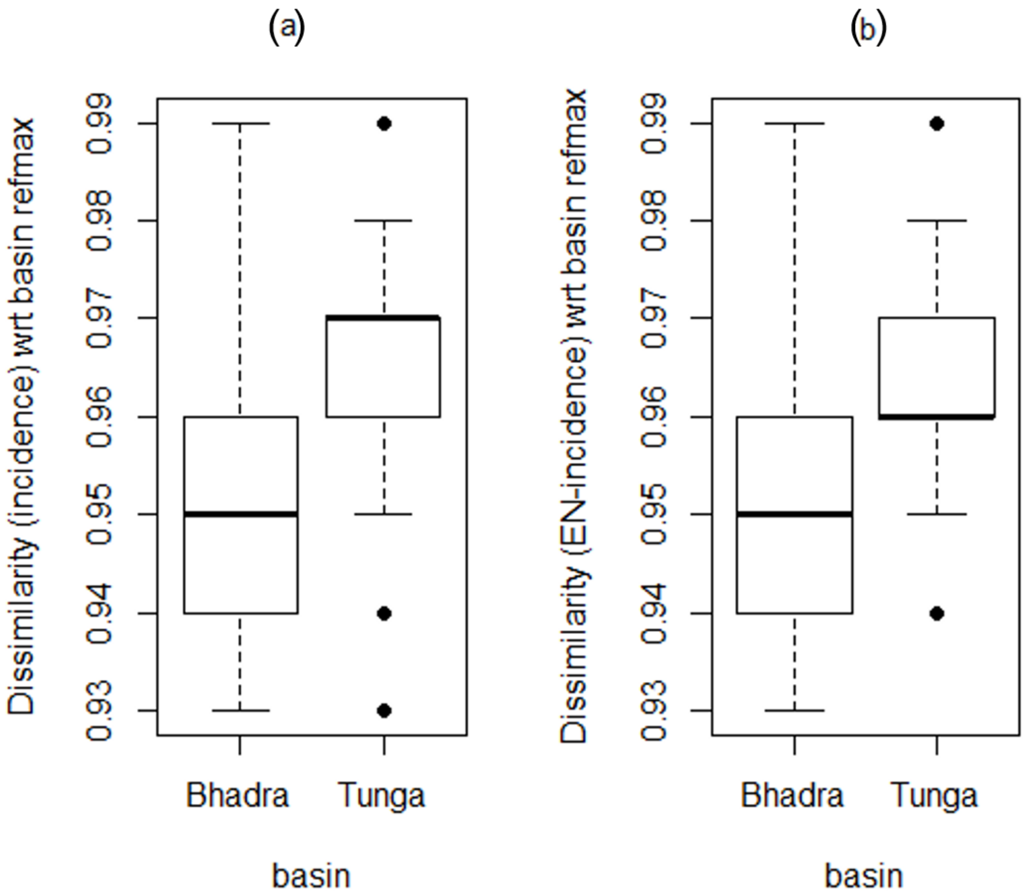
Freshwater fish species encountered in both Bhadra and Tunga sub-basins in Kudremukh National Park.

Total species	**Common species**	**Unique to Bhadra**	**Unique to Tunga**	**Bhadra species**	**Tunga species**
Paracanthocobitius mooreh	*Barilius bakeri*	*Garra stenorhynchus*	*Paracanthocobitius mooreh*	*Barilius bakeri*	*Paracanthocobitius mooreh*
Aplocheilus lineatus	*Barilius bendelisis*		*Aplocheilus lineatus*	*Barilius bendelisis*	*Aplocheilus lineatus*
Balitora mysorensis	*Barilius canarensis*		*Balitora mysorensis*	*Barilius canarensis*	*Balitora mysorensis*
Barilius bakeri	*Barbodes wynaadensis*		*Chanda nama*	*Barbodes wynaadensis*	*Barilius bakeri*
Barilius bendelisis	*Batasio sharavatiensis*		*Cirrhinus spp*	*Batasio sharavatiensis*	*Barilius canarensis*
Barilius canarensis	*Bhavania australis*		*Glyptothorax sp3*	*Bhavania australis*	*Barilius bendelisis*
Barbodes wynaadensis	*Botia striata*		*Hypselobarbus dobsoni*	*Botia striata*	*Barilius wynaadensis*
Batasio sharavatiensis	*Channa striata*		*Hypselobarbus jerdoni*	*Channa striata*	*Batasio sharavatiensis*
Bhavania australis	*Dawkinsia arulius*		*Mastacemeblus armatus*	*Dawkinsia arulius*	*Bhavania australis*
Botia striata	*Devario malabaricus*		*Mystus gulio*	*Devario malabaricus*	*Botia striata*
Chanda nama	*Garra bicornuta*		*Nemacheilus denisoni*	*Garra bicornuta*	*Chanda nama*
Channa striata	*Garra mullya*		*Nemacheilus semiarmatus*	*Garra mullya*	*Channa striata*
Cirrhinus spp	*Hypselobarbus curmuca*		*Nemacheilus triangularis*	*Garra stenorhynchus*	*Cirrhinus spp*
Dawkinsia arulius	*Osteochilus nashii*		*Ompok malabaricus*	*Hypselobarbus curmuca*	*Dawkinsia arulius*
Devario malabaricus	*Puntius sahyadriensis*		*Parambassis ranga*	*Osteochilus nashii*	*Devario malabaricus*
Garra bicornuta	*Rasbora daniconius*		*Parambassis thomassi*	*Puntius sahyadriensis*	*Garra bicornuta*
Garra mullya	*Salmophasia boopis*		*Pethia setnai*	*Rasbora daniconius*	*Garra mullya*
Garra stenorhynchus	*Tor khudree*		*Pethia striata*	*Salmophasia boopis*	*Glyptothorax sp3*
Glyptothorax sp3	*Xenentodon cancila*		*Pethia ticto*	*Tor khudree*	*Hypselobarbus curmuca*
Hypselobarbus curmuca			*Salmophasia novacula*	*Xenentodon cancila*	*Hypselobarbus dobsoni*
Hypselobarbus dobsoni					*Hypselobarbus jerdoni*
Hypselobarbus jerdoni					*Mastacemeblus armatus*
Mastacemeblus armatus					*Mystus gulio*
Mystus gulio					*Nemacheilus denisoni*
Nemacheilus denisoni					*Nemacheilus triangularis*
N. semiarmatus					*N. semiarmatus*

Total species	Common species	Unique to Bhadra	Unique to Tunga	Bhadra species	Tunga species
Nemacheilus triangularis					*Ompok malabaricus*
Ompok malabaricus					*Osteochilus nashii*
Osteochilus nashii					*Parambassis ranga*
Parambassis ranga					*Parambassis thomassi*
Parambassis thomassi					*Pethia setnai*
Pethia setnai					*Pethia striata*
Pethia striata					*Pethia ticto*
Pethia ticto					*Puntius sahyadriensis*
Puntius sahyadriensis					*Rasbora daniconius*
Rasbora daniconius					*Salmophasia boopis*
Salmophasia boopis					*Salmophasia novacula*
Salmophasia novacula					*Tor khudree*
Tor khudree					*Xenentodon cancila*
Xenentodon cancila					



Appendix 3.2 (a) Species dissimilarity with respect to combined basin reference maximum across Bhadra and Tunga and (b) species dissimilarity with respect to basin reference maximum for endemic species using incidence data. Species dissimilarity is higher in Bhadra than Tunga in both (a) & (b) panel.



Appendix 3.3 (a) Species dissimilarity with respect to the individual basin reference maximum using incidence data for all species and (b) for endemic species. Species dissimilarity is consistently higher in Tunga than Bhadra basin.

Appendix 4.1

Supporting Information on catchment details across four river sub-basins

S1 A Table. Catchment area

River Sub-basin	Area (km^2)	Direction of flow	Basin	State
Mhadei	425.96	West	Mhadei	Karnataka & Goa
Malaprabha	744.32	East	Krishna	Karnataka
Bhadra	225.12	East	Krishna	Karnataka
Tunga	160.00	East	Krishna	Karnataka

S1 B Table. Details of environmental variables measured in the study.

Variables	Units	Measurement details
Site characteristics		
Elevation		
Location (Lat. Long)	Degree decimal	GPS etrex Garmin
Water quality variables		
Water temperature	^{0}C	Thermometer
Electrical conductivity	μms^{-1}	Hanna Instruments - 98302
Total dissolved solids	parts per trillion	Hanna Instruments - 98304
pH	---	Hanna Instruments - 96107
Dissolved oxygen	mgL^{-1}	Winkler's titration method
Inorganic nitrates	mgL^{-1}	Spectro-photometry
Inorganic phosphates	mgL^{-1}	Spectro-photometry
Free CO_2	mgL^{-1}	water analysis in the lab
Calcium hardness	mgL^{-1}	water analysis in the lab
Total hardness	mgL^{-1}	water analysis in the lab
Total alkalinity	mgL^{-1}	water analysis in the lab
Stream characteristics		
Stream order (1:50,000)	1-5	Survey of India toposheet
Stream width	m	meter by using a measuring tape
Depth	m	average 3 depth readings along a stream width
Canopy cover	%	Visual estimation
Rocks	%	
Boulders	%	
Cobbles	%	
Pebbles	%	
Gravels	%	
Sand	%	
Leaves and woods	%	

Supporting Information - S2

Table1. Systematic list of fish species with multiple guild definitions of freshwater fish species sampled across regulated (RSB) and non-regulated sub-basins (NRSB) in the study area.

Order, Family, Species	Sub-basins	Basis of guild definition				
		Water column Position	Feeding Preferences	Flow response	Life history cues	Reproductive strategy
Cyprinodontiformes						
Aplocheilidae						
Aplocheilus lineatus	TN, ML	SD	Hetertrophic	Rheophilic	Opportunistic	Lithophils
Beloniformes						
Belonidae						
Xenentodon cancila	BH, TN	SD	Hetertrophic	Rheophilic	Intermediate	Phytophils
Cypriniformes						
Balitoridae						
Paracanthocobitius mooreh *	TN, ML	BD	Hetertrophic	Rheophilic	Periodic	Lithophils
*Balitora mysorensis**	BH, TN	BD	Phytophagous	Rheophilic	Periodic	Lithophils
*Bhavania australis**	BH, TN	BD	Omnivore	Rheophilic	Periodic	Psammophils
Mesonemacheilus sp*	TN	BD	Phytophagous	Rheophilic	Periodic	Lithophils
Nemacheilus denisoni	TN, ML, MH	BD	Omnivore	Rheophilic	Periodic	Lithophils
*Nemacheilus rueppelli**	ML	BD	Omnivore	Rheophilic	Periodic	Lithophils
*Nemacheilus triangularis**	BH, TN	BD	Phytophagous	Rheophilic	Periodic	Phytophils
*Nemacheilus semiarmatus**	TN	BD	Phytophagous	Rheophilic	Periodic	Lithophils
*Lepidocephalus thermalis**	ML, MH	BD	Phytophagous	Rheophilic	Periodic	Lithophils
Cobitidae						
Botia striata	BH, TN	BD	Omnivore	Rheophilic	Periodic	Psammophils
Cyprinidae						
*Barilius bakeri**	BH, TN	SD	Omnivore	Rheophilic	Periodic	Lithopelagophils
Barilius barna	TN	SD	Omnivore	Rheophilic	Periodic	Lithopelagophils

Order, Family, Species	**Sub-basins**	**Basis of guild definition**				
		Water column Position	Feeding Preferences	Flow response	Life history cues	Reproductive strategy
*Barilius canarensis**	BH, TN	SD	Omnivore	Rheophilic	Periodic	Lithopelagophils
Barilius bendelisis	BH, TN	SD	Omnivore	Rheophilic	Periodic	Lithopelagophils
Barilius sp	TN	SD	Omnivore	Rheophilic	Periodic	Lithopelagophils
*Barbodes wyanaadensis**	BH, TN	MCD	Omnivore	Rheophilic	Periodic	Psammophils
Cirrhinus fulungee	ML	MCD	Omnivore	Rheophilic	Periodic	Lithophils
Cirrhinus sp*	TN	MCD	Omnivore	Rheophilic	Periodic	Lithophils
Chela cachius	ML	MCD	Omnivore	Rheophilic	Periodic	Phytolithophils
*Devario malabaricus**	BH, TN, ML, MH	MCD	Heterotrophic	Rheophilic	Opportunistic	Phytolithophils
*Dawkinsia arulius**	BH, TN	MCD	Omnivore	Rheophilic	Intermediate	Phytophils
*Dawkinsia filamentosa**	MH	MCD	Omnivore	Rheophilic	Intermediate	Phytophils
*Garra bicornuta**	BH, TN, ML, MH	BD	Phytophagous	Rheophilic	Opportunistic	Lithopelagophils
*Garra mullya**	BH, TN, ML, MH	BD	Phytophagous	Rheophilic	Opportunistic	Lithopelagophils
*Garra stenorhynchus**	BH, ML, MH	BD	Phytophagous	Rheophilic	Opportunistic	Lithopelagophils
*Hypselobarbus curmuca**	BH, TN, ML	BD	Omnivore	Rheophilic	Periodic	Phytophils
*Hypselobarbus dobsoni**	TN, ML	BD	Phytophagous	Rheophilic	Periodic	Lithophils
*Hypselobarbus dubius**	ML	BD	Omnivore	Rheophilic	Periodic	Lithophils
*Hypselobarbus jerdonii**	BH, TN	MCD	Phytophagous	Rheophilic	Periodic	Lithophils
*Hypselobarbus thomassi**	BH, TN	MCD	Phytophagous	Rheophilic	Periodic	Lithophils
*Labeo fimbriatus**	ML	BD	Phytophagous	Limnophilic	Periodic	Lithophils
*Labeo porcellus**	ML	BD	Phytophagous	Limnophilic	Periodic	Lithophils
*Labeo spp**	TN	BD	Phytophagous	Limnophilic	Periodic	Lithophils
Oreichthys cosuatis	ML	MCD	Heterotrophic	Rheophilic	Periodic	Phytophils
*Osteochilius nashii**	BH, TN, ML	MCD	Omnivore	Rheophilic	Periodic	Lithophils
Pethia sp*	ML	MCD	Heterotrophic	Rheophilic	Intermediate	Phytophils

Order, Family, Species	Sub-basins	Basis of guild definition				
		Water column Position	Feeding Preferences	Flow response	Life history cues	Reproductive strategy
*Pethia setnai**	TN, ML, MH	MCD	Heterotrophic	Rheophilic	Intermediate	Phytophils
*Pethia striata**	TN	BD	Phytophagous	Rheophilic	Periodic	Phytophils
Pethia ticto	TN, ML	MCD	Omnivore	Eurytopic	Periodic	Phytophils
*Puntius amphibius**	ML, MH	MCD	Heterotrophic	Rheophilic	Intermediate	Phytophils
Puntius chola	ML	MCD	Omnivore	Rheophilic	Intermediate	Phytophils
Puntius dorsalis	ML	MCD	Phytophagous	Rheophilic	Intermediate	Phytophils
*Puntius sahyadriensis**	BH, TN, ML	MCD	Omnivore	Rheophilic	Intermediate	Phytophils
Puntius sophore	ML	MCD	Heterotrophic	Eurytopic	Periodic	Phytophils
Rasbora daniconius	BH, TN, ML, MH	MCD	Heterotrophic	Eurytopic	Opportunistic	Phytophils
Rasbora labiosa	ML, MH	MCD	Omnivore	Eurytopic	Opportunistic	Phytophils
*Rhohtee ogilbii**	TN	MCD	Phytophagous	Rheophilic	Periodic	Phytophils
Salmophasia bacaila	ML, MH	SD	Omnivore	Limnophilic	Periodic	Phytophils
Salmophasia boopis	BH, TN, ML, MH	SD	Heterotrophic	Limnophilic	Periodic	Phytophils
*Salmophasia novacula**	ML	SD	Heterotrophic	Limnophilic	Periodic	Phytophils
Schismatorhynchus nukta	ML	BD	Phytophagous	Rheophilic	Periodic	Lithophils
Systomus sarana sarana	ML	MCD	Phytophagous	Limnophilic	Intermediate	Phytophils
Systomus sarana subnastus	ML	MCD	Phytophagous	Limnophilic	Intermediate	Phytophils
*Tor khudree**	BH, TN, ML, MH	MCD	Omnivore	Rheophilic	Periodic	Lithophils
Mastacembeliformes						
Mastacembelidae						
Mastacembelus armatus	BH, TN	BD	Heterotrophic	Rheophilic	Equilibrium	Phytophils
Osteoglossiformes						
Notopreridae						
Notopterus notopterus	TN	BD	Omnivore	Rheophilic	Intermediate	Lithophils

Order, Family, Species	Sub-basins	Basis of guild definition				
		Water column Position	Feeding Preferences	Flow response	Life history cues	Reproductive strategy
Perciformes						
Ambassidae						
Parambassis ranga	TN, ML	MCD	Heterotrophic	Eurytopic	Intermediate	Phytophils
*Parambassis thomassi**	TN	MCD	Heterotrophic	Eurytopic	Intermediate	Phytophils
Chanda nama	TN	MCD	Heterotrophic	Eurytopic	Intermediate	Pelagophils
Channidae						
Channa gachua	ML	BD	Heterotrophic	Eurytopic	Equilibrium	Pelagophils
Channa micropeltis	ML	BD	Heterotrophic	Eurytopic	Equilibrium	Pelagophils
Channa punctata	ML	BD	Heterotrophic	Eurytopic	Equilibrium	Pelagophils
Channa striata	BH, TN, ML, MH	BD	Heterotrophic	Eurytopic	Equilibrium	Pelagophils
Cichlidae						
Etroplus suratensis	ML	BD	Omnivore	Eurytopic	Equilibrium	Lithophils
Gobidae						
Glossogobius guirus guirus	ML	BD	Heterotrophic	Eurytopic	Opportunistic	Lithophils
Sisoridae						
Glyptothorax sp2*	BH	BD	Heterotrophic	Rheophilic	Periodic	Lithophils
Glyptothorax sp3*	TN	BD	Heterotrophic	Rheophilic	Periodic	Lithophils
Glyptothorax sp4*	ML	BD	Heterotrophic	Rheophilic	Periodic	Lithophils
Siluriformes						
Bargidae						
*Batasio sharavatiensis**	BH, TN	BD	Heterotrophic	Eurytopic	Periodic	Phytophils
Mystus bleekeri	ML	BD	Heterotrophic	Eurytopic	Equilibrium	Phytophils
Mystus cavacius	ML	BD	Heterotrophic	Rheophilic	Periodic	Phytophils
Mystus gulio	TN, ML	BD	Heterotrophic	Rheophilic	Periodic	Phytophils
*Mystus keletius**	ML	BD	Heterotrophic	Rheophilic	Periodic	Phytophils

Order, Family, Species	Sub-basins	Basis of guild definition				
		Water column Position	Feeding Preferences	Flow response	Life history cues	Reproductive strategy
Claridae						
Clarias batrachus	ML	BD	Omnivore	Eurytopic	Opportunistic	Phytophils
Siluridae						
Ompok bimaculatus	ML	BD	Heterotrophic	Eurytopic	Periodic	Polyphils
*Ompok malabaricus**	TN	BD	Heterotrophic	Eurytopic	Periodic	Polyphils
Schilibidae						
*Eutropiichthys sp**	ML	BD	Heterotrophic	Rheophilic	Periodic	Phytophils

Note: SD – Surface dwellers, MCD – Mid-column dwellers, BD – Bottom dwellers, * indicate species endemic to the Western Ghats region
Regulated sub-basins: Malaprabha (ML), Mhadei (MH); Non-regulated sub-basins: Tunga (TN), Bhadra (BH).

Table 2. Literature review for fish guilds sampled in the study period.

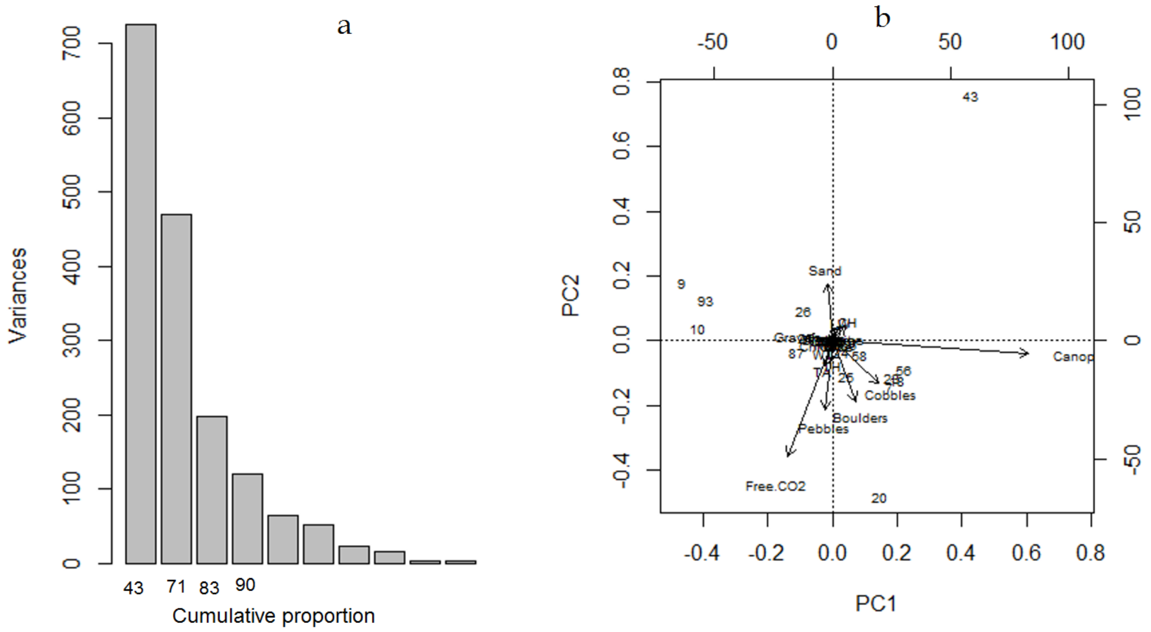
Guilds	**Guild definitions**	**References cited**
Water column position based guild	Bottom dwellers – commonly found at the bottom surface, Mid-column dweller – found in the mid-surface, Surface dweller – found near the surface	[59]. Lowe-McConnell RH. (1975). Fish communities in tropical freshwaters their distribution, ecology and evolution. London. [60]. Lowe-McConnell RH. (1987). Ecological studies in tropical fish communities. Cambridge University Press, Cambridge, Cambridge.
Feeding preference guilds	Heterotrophic consist of insectivores & carnivores, feed on benthic insect, snails and small fish. Omnivore feed on variety of food items such as food, leaves, insects etc. Phytophagous fishes consist of algivore, herbivore, detritivore feed largely on algae, fallen/decayed fruits & leaves.	[25]. Bhat A. (2002). A study of the diversity and ecology of Freshwater fishes of four river systems of the Uttara Kannada District, Karnataka, India. 178. [24]. Daniels RJR. (2002). Freshwater fishes of Peninsular India. University Press India (Pvt) Ltd, Hyderabad. [29]. Johnson J,Arunachalam M. (2012). Feeding habit and food partitioning in a stream fish community of Western Ghats, India. *Environmental Biology of Fishes* **93**: 51-60. [27]. Weliange WS,Amarsinghe US. (2007). Relationship between body shape and food habits of fish from three reservoirs of Sri Lanka. *Asian Fisheries Science* **20**: 257-270. [30]. Chakrabarty M, and S. Homechaudhuri. (2013). Fish guild structure along a longitudinally-determined ecological zonation of Teesta, an eastern Himalayan river in West Bengal, India. *Arxius de Miscel-lania Zoologica* **11**: 196-213
Flow-response guilds	Eurytopic means all life stages can occur both in lotic and lentic waters. Limnophilic consists of all life stages are confined to lentic water with macrophytes and rheophilic means that all life stages are confined to main river	[62]. Aarts BGW, Nienhuis PH. (2003). Fish zonations and guilds as the basis for assessment of ecological integrity of large rivers. Hydrobiologia 500:157-178

	channel.	[30]. Chakrabarty M, and S. Homechaudhuri. (2013). Fish guild structure along a longitudinally-determined ecological zonation of Teesta, an eastern Himalayan river in West Bengal, India. *Arxius de Miscel-lania Zoologica* **11**: 196-213 [45]. Das MK, Sharma AP, Vass KK, Tyagi RK, Suresh VR, Naskar M,Akolkar AB. (2013). Fish diversity, community structure and ecological integrity of the tropical River Ganges, India. *Aquatic Ecosystem Health & Management* **16**: 395-407.
Life-history cue-related guilds	Equilibrium strategists are fishes with small to medium body size, small clutch, high parental care & juvenile survivorship with intermediate maturity, opportunistic includes small body size, early maturity, continuous reproduction, small clutch size & little parental care, periodic /seasonal strategists include fishes with large body size, high fecundity, low juvenile survivorship, no parental care and late maturation and intermediate strategists include fishes with small body size, prolonged and distinct seasonal reproduction	[63].Welcomme RL. 1985. River Fisheries. FAO. 330. [64]. Welcomme RL, Winemiller KO,Cowx IG. (2006). Fish environmental guilds as a tool for assessment of ecological condition of rivers. *River Research and Applications* **22**: 377-396. [30]. Chakrabarty M, and S. Homechaudhuri. (2013). Fish guild structure along a longitudinally-determined ecological zonation of Teesta, an eastern Himalayan river in West Bengal, India. *Arxius de Miscel-lania Zoologica* **11**: 196-213
Reproductive strategy guilds	Lithophils includes rock & gravel spawners, lithopelagophils means rock, gravel spawners with pelagic larvae, Phytolithophils means non-obligatory plant spawners, phytophils means obligatory plant spawners, Pelagophils means pelagic spawners, polyphils includes obligatory plant and psammophils consist of sand spawners.	[62]. Aarts BGW, Nienhuis PH. (2003). Fish zonations and guilds as the basis for assessment of ecological integrity of large rivers. Hydrobiologia 500:157-178 [30]. Chakrabarty M, and S. Homechaudhuri. (2013). Fish guild structure along a longitudinally-determined ecological zonation of Teesta, an eastern Himalayan river in West Bengal, India. *Arxius de Miscel-lania Zoologica* **11**: 196-

		213 [45]. Das MK, Sharma AP, Vass KK, Tyagi RK, Suresh VR, Naskar M,Akolkar AB. (2013). Fish diversity, community structure and ecological integrity of the tropical River Ganges, India. *Aquatic Ecosystem Health & Management* **16**: 395-407.

Supporting Information - S3.

S3 Figure 1. Principal Components Analysis for selection of environmental variables for further regression analyses: (A) Scree plot showing proportion of variance explained for the first four Principal Components and (B) Bi-plot showing correlations between different variables along PC axes.



(C) PCA loadings for environmental variables

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14	PC15	PC16	PC17
Tot.alk	-0.04	-0.15	0.04	-0.07	0.09	-0.26	0.12	0.29	0.61	-0.58	0.13	-0.08	-0.12	0.24	-0.02	0.00	0.00
Free.co2	-0.21	-0.67	0.47	0.22	0.23	0.06	0.25	0.23	-0.17	0.11	-0.18	-0.01	0.01	-0.05	0.01	0.00	0.00
Chloride	-0.02	-0.02	0.04	0.02	-0.07	-0.02	-0.05	0.14	0.07	-0.24	0.28	0.33	0.35	-0.76	0.14	0.01	0.00
Cal.hard	0.06	0.09	-0.06	-0.08	0.04	-0.11	-0.04	0.01	-0.24	-0.44	-0.60	-0.49	0.26	-0.21	0.04	0.00	0.00
Tot.hard	0.00	-0.11	0.04	0.14	-0.10	0.38	0.44	-0.70	0.12	-0.30	0.11	-0.06	0.10	0.01	0.00	0.00	0.00
Inorg.N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	-0.03	0.00	0.01	-0.02	-0.17	-0.98	-0.07	-0.03
Diss.oxy	0.01	-0.02	0.02	0.02	-0.01	-0.08	-0.03	0.06	-0.01	0.06	0.11	0.09	0.87	0.45	-0.10	-0.02	0.00
Discharge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.14	-0.94
DW.ratio	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	-0.07	0.99	0.13
Wat.temp	0.00	-0.20	-0.11	-0.28	0.01	-0.09	-0.06	-0.08	-0.55	-0.45	0.01	0.52	-0.16	0.23	-0.03	0.00	0.00
TDS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.02	0.32
Cancov	0.93	-0.06	0.34	0.00	0.03	-0.06	0.00	-0.02	-0.01	0.00	0.03	0.03	-0.02	0.00	0.00	0.00	0.00
Rocks	0.00	-0.02	0.04	0.06	0.07	0.29	-0.22	0.19	-0.35	-0.20	0.62	-0.51	-0.04	0.05	-0.01	0.00	0.00
Boulders	0.11	-0.37	-0.27	-0.55	0.27	0.50	-0.23	0.00	0.25	0.11	-0.10	-0.02	0.09	-0.06	0.01	0.00	0.00
Cobbles	0.22	-0.26	-0.61	0.06	-0.32	-0.05	0.51	0.31	-0.12	0.12	0.06	-0.10	0.00	-0.04	0.00	0.00	0.00
Pebbles	-0.03	-0.41	-0.12	-0.11	0.05	-0.63	-0.21	-0.45	0.01	0.16	0.23	-0.25	0.02	-0.12	0.01	0.00	0.00
Gravels	-0.13	0.01	0.42	-0.62	-0.60	-0.02	0.17	0.06	-0.02	0.09	0.05	-0.14	0.01	-0.01	0.00	0.00	0.00
Sand	-0.02	0.32	0.03	-0.36	0.62	-0.16	0.54	0.01	-0.13	0.11	0.17	-0.04	0.04	-0.08	0.01	0.00	0.00

Appendix – 5.1

Copeia

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A New Species of *Pethia* from the Western Ghats, India (Teleostei: Cyprinidae)

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, K. Rema Devi
, and J. Krishnaswamy

Received: December 18, 2012; **Accepted:** December 12, 2014

;

Published: May 4, 2015

[+] Author & Article Info

Pethia striata, new species, is described from the Tunga River in Kudremukh National Park, in the central part of the Western Ghats, Karnataka State, India. The new species is distinguished from its congeners by the combination of the following characters: absence of barbels; stiff and serrated last unbranched dorsal-fin ray; complete lateral line with 20–21 pored scales and a relatively small humeral spot one scale below the fourth lateral-line scale; a large black blotch covering lateral-line scales 17–19. In addition, the outer edges of body scales are dark, producing a striped pattern along the sides of the body. *Pethia striata*, new species, is presently known only from headwater-streams of the Tunga River basin.

Appendix – 5.2

River Research and Applications

RESEARCH ARTICLE

Assessing the recovery of fish assemblages downstream of hydrological barriers in India's Western Ghats

Authors

V. Atkore., N. Kelkar and J. Krishnaswamy

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Abstract

River flow regulation by dams and barrages threatens freshwater fish diversity globally. However, factors contributing to the recovery of fish communities downstream of barriers to river flow are not well understood. It is crucial to identify processes that might enable river restoration despite the presence of river barriers. In this study, we assess recovery of fish species, including endemics, downstream of large and small barriers in the Malaprabha basin in the Western Ghats of India. We define "fish species recovery" as the proportion of fish species occurring in river reaches downstream of barriers, of the species pool occurring in upstream unregulated segments with similar elevation, stream order, and habitat characteristics. As per the serial discontinuity concept, we predicted that recovery will reduce immediately after, but gradually increase with, increasing distance downstream of barriers, due to contributions from unregulated streams joining the river. As expected, fish recovery decreased immediately downstream of barriers and increased at greater distances and declined when the number of upstream barriers increased, indicating cumulative impacts. Dissolved oxygen and total alkalinity were positively and negatively correlated with both recovery and distance from barrier. Water temperature and rocky instream habitat influenced recovery positively, but independent of distance from barriers. Recovery of fish species, including Western Ghats endemics, was promising even under the current level of river regulation in the area, mainly due to connectivity with undammed tributaries. Strict limits on future stream regulation within already regulated basins will be critical for conservation of freshwater fish biodiversity in this region.