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# Evaluation of aquatic ecological systems through dynamics of ichthyofaunal diversity in a Himalayan torrential river, Murti

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ABSTRACT

The biodiversity hotspot region of the Eastern Himalayas consists of a vast freshwater network enriched with species diversity. Many small-scale torrential rivers and water reaches contribute to the species pool of all the major rivers by converging downstream. These reaches are most likely to be degraded at a faster rate as compared to the large-scale rivers following an increased rate of urbanization, habitat alterations, and changing climatic conditions. Therefore, this study aims to explore River Murti, which is a representative small scale river system characterized by a large altitudinal gradient and a diverse watershed area. Ichthyofaunal diversity (i.e., diversity, evenness & richness) and 21 environmental variables are measured through a tri-seasonal sampling effort conducted along 14 selected locations. A total of 41 fish species (including species belonging to 4 Near Threatened, 8 Vulnerable, and 1 Endangered) are found inhabiting this river. Ichthyofaunal assemblage is found to be primarily modulated by habitat diversity and landscape variables. Three Aquatic Ecological Systems (AES) have been identified along this river in a top-down approach based on recorded environmental variables. We have calculated an observed/expected ratio for each diversity indices along 14 locations based on predicted temporal variability using boosted regression (BRT) models. The evaluation of diversity status has been kept at 0.5 to account for a 50% loss or deviation from observed (O/E50). This evaluation has been successfully used to delineate AES1 with majorly "Impaired" status and thus ensures its importance in terms of species conservation. Our study indicates the contribution of 11 major environmental drivers modulating the species assemblage patterns in these AES. Amongst them, altitude, substrate coarseness, river morphology, and shelter availability are strongly associated with species diversity as per the BRT models. These underlying factors are also correlated with "basin pressure," suggesting that anthropogenic disturbances, as well as the changing climate, might play an important role in the gradual change in environmental conditions, which in turn could cause a shift in species assemblage structure.

## 1. Introduction

The Eastern Himalayan global biodiversity hotspot spreads across Nepal to Myanmar, through the north-eastern part of India including Dooars-North Bengal region (82.70 °E and 100.31 °E longitude and 21.95 °N to 29.45 °N latitude) and covering a total area of 524,190 sq.km (Chettri et al., 2010). A vast network of freshwater tributaries has been draining this region due to the characteristic landscape, climatic conditions, and tectonic lift, which in turn supports the flourishing biodiversity in both the terrestrial and aquatic systems. Following the same, this region is also considered as an 'Ecologically Sensitive Area' (ESA) (Kapoor et al., 2009). The headwaters of most of the crucial antecedent rivers of North Bengal lie within these high hills of the Eastern Himalaya. Many small-scale waterfalls, hill-streams, and torrential rivers with specific geomorphological and ecological features (Mukherjee et al., 2009; Rudra, 2018) contribute significantly to these headwaters (Chapman and Rudra, 2015; Rudra, 2014). Since the freshwater-species diversity shows the lowest 'Living Planet Index' (McRae et al., 2017), conservation of fishes is a priority in this region due to its vulnerability to predicted climate change (Heino et al., 2009). Among the 1073 reported freshwater species from the Eastern Himalayan region, ichthyofaunal diversity dominates with 520 taxa (Allen et al., 2010). However, according to the International Union for Conservation of Nature (IUCN) reports, 7.2% of the total reported freshwater taxa are evaluated as threatened and 5.4% as near threatened. Nevertheless, the report has suffered a scarcity of information (Allen et al., 2010) to date.

The freshwater riverine status of North Bengal has been evaluated as

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the most prioritized freshwater conservation area among the Himalayan region (Bhatt et al., 2016), including the lower parts of River Teesta, Balasan, Lish, Gish, and Murti (Patra et al., 2017). River Teesta has been the center of interest, regarding the representation of the overall status of piscine diversity and riverine health of this region (Bhatt et al., 2016; Chakrabarty and Homechaudhuri, 2013; Jayaram and Singh, 1977) followed by few other rivers, i.e., Jaldhaka and Torsha (Mahapatra et al., 2014; Sarkar and Pal, 2018). However, the investigations on torrential headwaters and small scale rivers have been neglected. In contrast, being the major contributors to these large-scale rivers and vast freshwater networks of North Bengal, they all have skewed hydrological characteristics, environmental drivers (Rudra, 2018). Lately, the spatial pattern of urbanization along the Himalayas is being altered at an increased rate (Singh, 2015). In a recent report (Tiwari et al., 2018), a shift of urbanization patterns has been indicated from mid-slopes, ridges to higher elevations, extending up to the valleys., thereby posing potential threats upon biodiversity and natural resources.

River Murti has originated from the Mo forest belonging to the Neora Valley National Park in the Darjeeling Himalayas at an altitude of 2211 m (Chakraborty and Datta, 2013; Kar et al., 2014; Kundu et al., 2019). It features the typical characters of an antecedent river of North Bengal, i.e., monsoon rain, primarily contributing to their discharge while snow-melt water in the summer months (Rudra, 2016). The river traverses 47.5 km before its confluence with a sizeable Himalayan river, Jaldhaka near Gorumara National Park (Chakraborty and Datta, 2013; Chakraborty and Mukhopadhyay, 2014; Kar et al., 2014). Being an inland river, it has 41 sq.km-approximated catchment area with a perimeter of 33 km (Kar et al., 2014), and its width varies from 15.25 to 475.5 m as measured in this study. This river has less than 5% contribution in annual discharge in comparison to the major rivers, i.e., River Teesta (Arfanuzzaman, 2018). A few reports are available on the eco-physiology of selected ornamental fishes inhabiting this river (Chaudhuri et al., 2017; Kundu et al., 2019; Mukhopadhyay and Bhattacharjee, 2018, 2019), but a full-scale status of the ichthyofaunal diversity and the subsequent relationship with their environment remain unexplored.

Since these upland water reaches are data deficient, this study aims to explore the ichthyofaunal diversity from River Murti, a representative of torrential small-scale water reaches of Terai-Dooars-North Bengal region. The Nature Conservancy (TNC) has successfully implemented a four-tiered hierarchical classification in conjunction with species composition and its ecosystem, i.e., Aquatic Zoogeographic Units (AZU) (1:26,000,000), Ecological Drainage Units (EDU) (1:26,000,000), Aquatic Ecological Systems (AES) (1:4,000,000) and Microhabitats (1:1,200,000) for freshwater systems (Higgins et al., 2005). Based on that, a coarse conservational assessment is applied in a top-down approach to demarcate out Aquatic Ecological System (AES) (Higgins et al., 2005) following the recorded environmental variables and their similarities in a broader context (Khoury et al., 2011). This approach is necessary to address the role of physical environment and abiotic factors in shaping a more local distribution of species (Higgins et al., 2005). Since sufficient geographic information system-data about this river is lacking, the top-down approach could serve as an interesting and unique method in defining the prominent AES based on similar environmental attributes (Higgins et al., 2005). The spatial-temporal variation of fish assemblage along the AES and the critical environmental drivers determining the species assemblage have been studied. Furthermore, using predictive models, this investigation attempts to address the basis of species assemblage and quantitatively evaluate the AES for their temporal impairment. Therefore, this study focuses on providing a predictive measure of ichthyofaunal diversity and attempts to prioritize the AES with its characteristic inhabitant species.

## 2. Methods

### 2.1. Study sites

Unlike most rivers of North Bengal, which have originated from the Himalayas and drains the northern fans, River Murti has a confined course and traverses over uplifted blocks of the Terai-Dooars region (Bandyopadhyay et al., 2014; Guha et al., 2007). It flows through mid-altitude and intermediate fan surfaces following two instances that are characterized by significant structural controls, namely Matiali scarp in the North and Chalsa scarp in the south (Chakraborty and Mukhopadhyay, 2014; Goswami et al., 2012b). Thus, while traversing, it encompasses four different types of terrains, i.e., high hills, hills, rocky, and finally, debouching into the plains by creating characteristic fans (Mukherjee et al., 2009; Rudra, 2018). There has been a major Himalayan tectonic thrust along the Neora–Jaldhaka valley, including the Murti river-bed, which might have resulted in the recurrence of high and low flow regimes (Chakraborty and Mukhopadhyay, 2014; Goswami et al., 2012b; Guha et al., 2007). A pronounced temperature gradient in the water (Bandyopadhyay et al., 2014) allows a vast assemblage of cold & warm-water species in this river.

Seven sites, 7–10 km apart (Angermeier and Karr, 1983) (Fig.1), were selected, addressing the considerable variations in terrains, riparian contribution, and differential flow regimes along with the decreasing altitude of River Murti, to delineate the AES. In each site, studies were conducted in two locations (Appendix B), representative of riffle and pool conditions, respectively, to account for the maximum variation in the ichthyofaunal diversity adequately. All of the sampling sites were considerably placed outside the protected area, where local exploitation of the river resources could be observed.

### 2.2. Sampling

The study had been conducted in a tri seasonal frame (Pre-Monsoon, Monsoon, and Post Monsoon) from April 2016 to April 2018. Freshwater fish abundance was recorded by applying a unified single-pass electrofishing method with 1020 NP ultrasonic inverter electro fisher-fish machine shocker connected to a 12-volt power system, followed by a current net (mesh size 2.5 X 2.5 cm). The removal method of estimation was applied, and consecutively three efforts (Bohlin et al., 1989) had been applied for each sampling attempt to a total stretch of 90 m (upstream & downstream). All the immobilized fishes (Bohlin et al., 1989) were identified up to species level according to Jhingran and Talwar (1991) & Fish Base (www.fishbase.org) (Froese and Pauly, 2011) and released as quickly as possible to the same spot. The observed mortality rate for the captured fishes was 7%, with a single individual per species being preserved in a 10 % formalin solution.

Twenty-one environmental variables were recorded to assess five substantial characteristics considering the area, ecosystem, and focal species-specific attributes (Edwards and Huryn, 1996; Hauer and Lamberti, 2011; Pettorelli et al., 2011; Poiani et al., 2000). These were namely water quality, climate profile, habitat diversity, landscape features, and basin pressure of the study sites, as listed in Table 1.

### 2.3. Statistical analysis

Statistical analysis was performed in PRIMER-E-version 6.1.18 (https://www.primer-e.com/) (Clarke and Gorley, 2006) and the R Platform (R Studio Team, 2015; http://www.rstudio.com) (Team, 2015, 2018) with packages namely, “betapart”, “BiodiversityR”, “ggplot2″, “vegan”, “grid”, “effects”, “DEseq2″, “plyr”, “scales”, “reshape2″, “FactoMineR”, “factoextra”, “corrplot”, “car” “visreg”, “gbm”, “dismo” and “pROC”. In terms of data pre-treatment, a primary square-root transformation was applied to the species abundance data. In contrast, a log transformation was applied to the environmental variables (Clarke and Gorley, 2006) and checked for normality using the

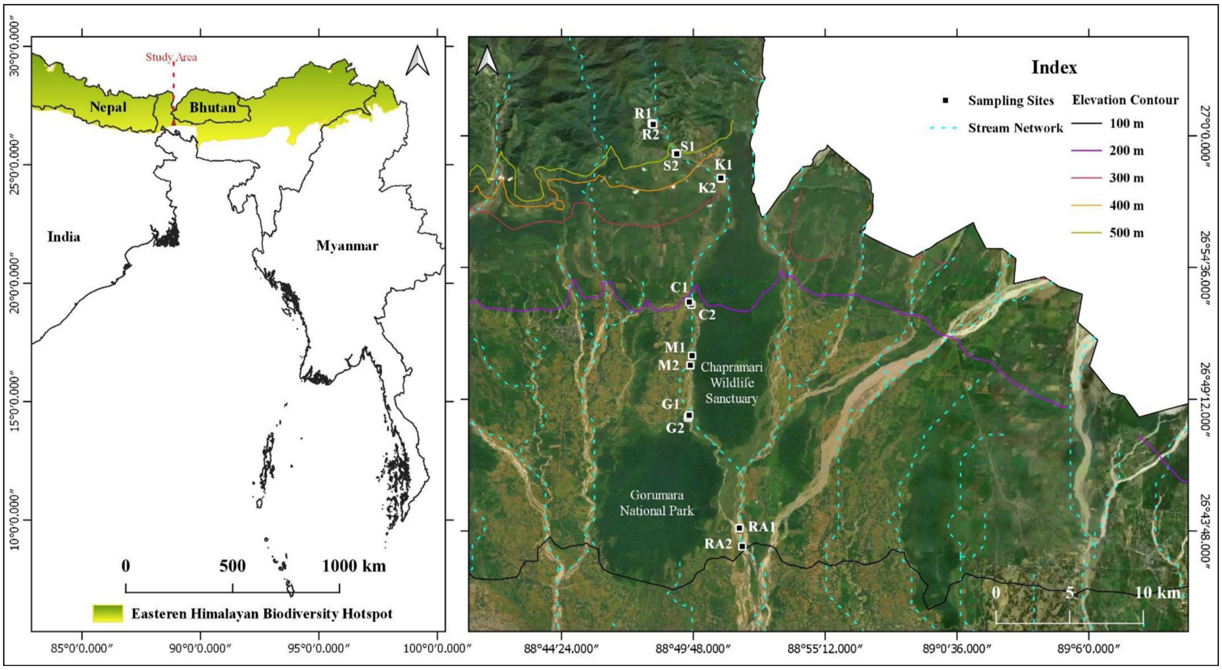



**Fig. 1.** Study sites along the longitudinal gradient of River Murti, Terai-Dooars region of Eastern Himalayas. See site-coordinates in Appendix B.

Shapiro test (Appendix B). An analysis of similarities (ANOSIM) test was employed to assess the significance of differences among the species assemblage between riffle and pool regimes, considering the 14 locations in this study (Appendix A).

### 2.3.1. Ichthyofaunal Diversity

A species accumulation curve (Clarke and Gorley, 2006; Colwell and Coddington, 1994) with eight S-extrapolators (Sobs, Chao1, Chao2, Jacknife1, Jacknife2, Bootstrap,MM, and UGE) was plotted to find out maximum probable occurrence ($S_{max}$) of fishes in this river followed by a rank abundance curve. The α diversity analysis was conducted on transformed abundance data by using the DIVERSE function (Clarke and Gorley, 2006; Kindt and Coe, 2005), to calculate site-wise richness (Margalef), evenness (Pielou's Evenness) and diversity indices (Shannon's H). A β diversity output was generated, accounting for both the beta replacement and turnover (Baselga and Orme, 2012) of species assemblage in the river.

### 2.3.2. Delineation of AES

Initially, an ANOSIM test (Clarke and Gorley, 2006) was performed to find out the significance of spatial and temporal variation in species assemblage as well as in the environmental frame for the 14 sampling locations. Following this, a correspondence analysis (CA) (Borcard et al., 2011; Ter Braak, 1986; Kindt and Coe, 2005) was performed

**Table 1**
List of 21 environmental variables recorded from the River Murti.

| Variable Class | Recorded variables | Following Standard Protocol/Kit | Min. | Max. | Mean |
|---|---|---|---|---|---|
| Water Quality | Water Current (m $sec^{-1}$) | Propeller type water current meter (Lawrence & Mayo) | 0.015 | 0.9212 | 0.312309405 ± 0.264833423 |
| | Dissolved Oxygen (mg $l^{-1}$) | Water Ecology Kit, Hach Model AL-36B Kit 180202 | 7.4 | 17.2 | 11.30238095 ± 2.791077703 |
| | Dissolved $CO_2$ (mg $l^{-1}$) | Same | 5 | 15 | 8.452380952 ± 3.638498174 |
| | pH | Same | 6.66 | 9.59 | 8.064434524 ± 0.87094364 |
| | Total Acidity (mg $l^{-1}$) | Same | 0 | 6.84 | 3.610952381 ± 2.965864274 |
| | Total Alkalinity (mg $l^{-1}$) | Same | 0 | 41.04 | 19.21714286 ± 12.76233659 |
| | Water Hardness (mg $l^{-1}$) | Same | 17.1 | 34.2 | 25.84880952 ± 8.594289138 |
| | TDS (mg $l^{-1}$) | OAKTON Multiparameter PCSTestr 35 | 14.2 | 46.3 | 30.85897619 ± 7.985083093 |
| Landscape Features | NDVI | ISRO-Bhuvan Database (1:320,000) (https://bhuvan.nrsc.gov.in/bhuvan_links.php) | 0.235 | 0.615 | 0.488214286 ± 0.1263473 |
| | QBR INDEX | Following (Colwell, 2007) | 20 | 120 | 62.14285714 ± 24.98536577 |
| | Stream Order | Hydrology map (1:66,667) | 4 | 5 | 4.428571429 ± 0.497843888 |
| | Altitude (m) | Garmin eTrex GPS | 85.98 | 483 | 244.1050286 ± 141.7637739 |
| | Distance from Jaldhaka River (m) | Garmin eTrex GPS | 186 | 6511 | 4394.857143 ± 2082.032702 |
| Basin Pressure | Pressure Index | Following (Hermoso, Linke, et al. 2009) | 4 | 15 | 9.678571429 ± 4.180161737 |
| Habitat Diversity | Water Depth (m) | Measuring rod and tapes | 0.001 | 5.2 | 1.825297619 ± 1.675450177 |
| | Substrate Coarseness | Following (Wentworth, 1922) | 3 | 20 | 10.60714286 ± 5.314263274 |
| | River Width (m) | Measuring rod and tapes | 3.16 | 25.887 | 16.19057143 ± 7.50587288 |
| | Shelter Availability (sq.km) | Following (Beisiegel, 2006) | 0 | 0.15473 | 0.152214684 ± 0.129102609 |
| Climate Profiles | Air Temp (°c) | OAKTON Multiparameter PCSTestr 35 | 13 | 35.5 | 25.33547619 ± 6.361705728 |
| | Annual Precipitation (mm) | Indian Meteorological Survey Data (www.imd.gov.in/pages/services_hydromet.php) | 0 | 1021 | 288.5761905 ± 374.6446463 |
| | Water Temp (°c) | OAKTON Multiparameter PCSTestr 35 | 10 | 32.4 | 22.99166667 ± 5.888035824 |

¶ TD: Total Dissolved Solid, ND: Normalized Difference Vegetation Index, QBR: Qualitat del Bosc de.

upon the fish species assemblage pattern. Next, to classify and demarcate the AES regarding the temporal and spatial dynamicity of environmental drivers, a SIMPROF (Similarity Profile Analysis) clustering (Clarke and Gorley, 2006) was employed based on the similarity in the available environmental attributes (Higgins et al., 2005). The spatial and temporal variability of species assemblage within and between AES were subsequently analyzed through ANOSIM test and projected within nonmetric multidimensional (nMDS) plots (Clarke and Gorley, 2006; Kindt and Coe, 2005; Kindt and Kindt, 2018).

#### 2.3.3. Predictive Modelling

A RELATE test with Spearman rank correlation method (Clarke and Gorley, 2006) was performed to assess the significance of recorded environmental variables in determining the fish assemblage pattern in this river.

*2.3.3.1. Predictor Variables*. Based on the results of the RELATE hypothesis, a principal component analysis (PCA) was performed (Clarke and Gorley, 2006; Kindt and Coe, 2005), addressing differences among the sites leading to the delineation of AES. On the other hand, significant variables addressing the species assemblage pattern were estimated in a combination of ordination (Adonis) (Oksanen et al., 2013; Torondel et al., 2016) and spearman correlation-based global analysis (BEST) (Clarke and Gorley, 2006). Therefore, considering both the analysis, addressed to the temporal variability of ichthyofaunal biodiversity and environment, an ultimate combination of predictor variables were selected and fitted in the predictive models (Cumming and Wooff, 2007; Efird and Konar, 2014; Jolliffe, 2003; Paliy and Shankar, 2016; Skovgaard, 2000). Also, Pearson's correlation was calculated to sort out strongly correlated variables with basin pressure, which were further imposed for the relative influence of predictor variables in selected predictive models.

*2.3.3.2. Response Variables*. Three indices were considered, i.e., richness (Margalef), evenness (Pielou's Evenness), and diversity (Shannon's H) as response variables for predictive modeling. These models would cumulatively account for the complete scenario of piscine diversity in terms of composition, rarity, commonness, and relative abundance of all species.

*2.3.3.3. Model fitting and prioritization of AES*. The boosted regression trees (BRT) has already been proved to be an excellent predictive modeling tool instead of fitting a single best model (Elith et al., 2008). Depending upon the small size of the data set, tree complexity was kept at 2, i.e., a tree might maximally have two splits. Following the best suggestions for small data set handling in BRT (Elith et al., 2008), the learning rate was varied for three responses to achieve the fastest of 1000 trees in a model. The ten-fold cross-validation (CV) was used to maximize the predictive performance of the optimum number of trees. So cumulatively, a low learning rate with cross-fold validation was used for the reliability of the model's performance (Elith et al., 2008). In this study, the CV correlation means of selected models were considered > 0.5 to address its robustness and informative properties (Francis et al., 2011).

Three BRT models were fitted for the response variables against the same set of predictor variables of year 1 data (2016-17). Along with the relative influence of the predictors, the best trees had predicted the response for year 2 (2017-18), addressing significant seasonal-annual variation in sampling sites. Based on these expected responses, the AESs were evaluated for this river at the level of observed/ expected ratio = 0.5 (OE50). It would account for a 50% loss or deviation from the observed diversity status to suffice a coarse approach of conservation. This method has been used coarsely in a large number of studies addressing species loss and depletion of biodiversity while maintaining the threshold level at 50% (Hermoso et al., 2009; Linke and Norris, 2003; Noss, 2004).

Furthermore, this calculated ratio had been diffused in a checkerboard, which was prepared to give more weights on the impaired values from the level of threshold. In this checkerboard, a cell with the calculated value of O/E = 0.5 had been given a value of 0.5, O/E > 0.5 had been given a value of 0 and the value of O/E < 0.5 had been given a value of 1. The inference for a site was set at the value of 3 as it would address a minimum of three incidences of impairment in the observed scenario. Therefore, a value of three or more than three would indicate 'Impaired' status for a particular site. In contrast, the 'With Concern' status was given to a value of 2 to 2.5, and the rest of them would be treated with 'Good' status. However, in the context of AES, the inference had been set at 6, indicating the inclusion of at least two impaired sites. Based on the species heat map, the common and site-specific species were identified for the concerned sites belonging to the impaired AES.

## 3. Results

### 3.1. Ichthyofaunal diversity

A total of 3906 individuals (Appendix A) belonging to 41 species have been recorded (Table 2), with an average catch per location being 142 ± 53. The species accumulation curve (Appendix A) has predicted the total number of species inhabiting this river to be 44.84 ($S_{Max}$), which suggests that the expected number does not project much deviation from the recorded sampling size of this study. A total of 15 families belonging to 4 orders of fishes have been identified (Table 2), among which the Cyprinids are dominant, followed by fish species from the Nemacheilidae family(Appendix A). According to IUCN, four of them are listed as 'Near-Threatened (NT)' category; one species is 'Not Evaluated (NE),' whereas the rest of them are in the 'Least Concerned (LC)' category. A rank abundance curve (Appendix A) indicates three dominant species of River Murti, namely *Acanthocobitis botia* of Nemacheilidae family with *Barilius bendelisis* & *Puntius chonchonius* of Cyprinid family. Three diversity indices, i.e., richness (Margalef), evenness (Pielou's Evenness), and diversity (Shannon's H) along with the total number of individuals (N) have indicated an increasing trend of diversity in sites, M2 & K2 (Appendix A). A β-diversity analysis shows species turnover to be a significant component of this river. The prominent turnover axis is observed between two groups of sites, i.e., G1-G2-RA1-RA2 & rest of the other sites (Appendix A).

### 3.2. Aquatic ecological systems (AES)

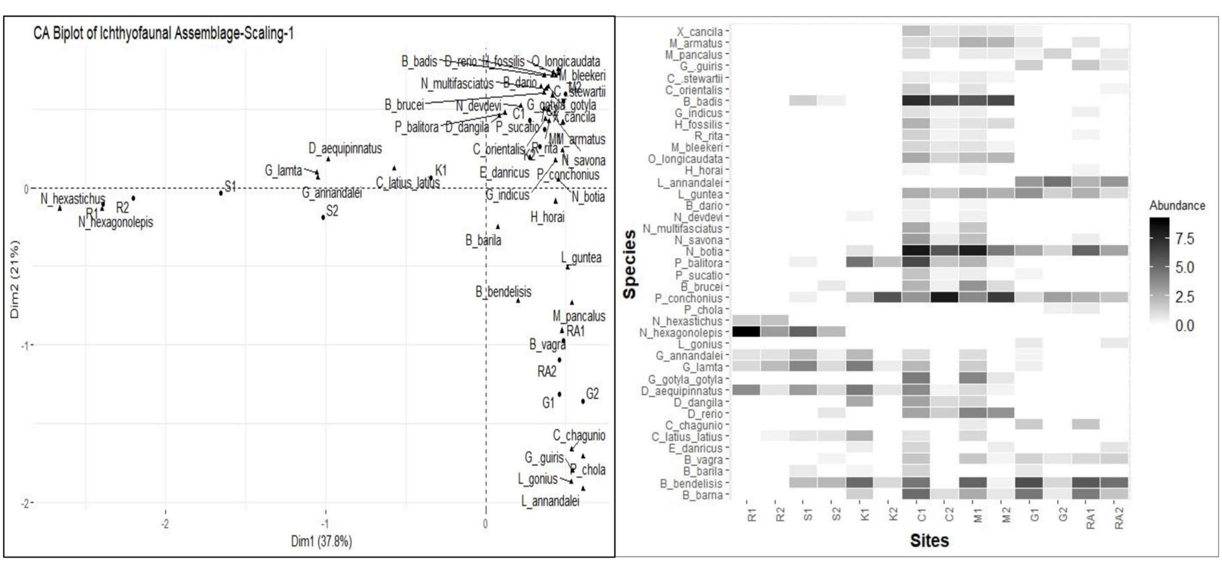
The species assemblage structure of River Murti has a distinct spatial pattern, while it is not significant at the temporal scale (Appendix A). The correspondence analysis (CA) (Appendix A) has listed out 18 of the 41 recorded species as the significant contributors to variance (explaining 71.9%, see Appendix B), due to their rarity or site-specific occurrences (Fig.2a).

However, sampling sites have significant spatial and temporal variability based on their environmental attributes (Appendix A). The SIMPROF test has clustered the sampling sites regarding season, with a minimum significant cluster distance being 3.02 (Fig.3a). Having considered the loss of variation in monsoon, the sites of this upland river are grouped, considering high similarity clustered distance, i.e., 4 (Fig.3b) and delineated as a single AES. Thus, three AESs are identified, i.e., AES 1 with R1, R2, S1, S2, K1, K2, AES 2 with C1, C2, M1, M2, G1, G2 and AES 3 with RA1, RA2. On the contrary, site K1, K2 & C1, C2 have exhibited differential temporal similarity with both the AES1 and AES2.

Following the ANOSIM test (Appendix A), the spatial variation of species assemblage along the AES is found to be significant. In contrast, the inter-annual and inter-seasonal variation in species assemblage is not significantly influential. However, the overlaps in the seasonal assemblage among the AES consider the occurrences of common and

**Table 2**
List of 41 fish species recorded from the River Murti. (LC: Least Concerned, EN: Endangered, VU: Vulnerable, NT: Near Threatened, NE: Not Evaluated).

| Family | SL No | Scientific Names (Talwar and Jhingran, 1991) (Rectified as per Fish base & IUCN) | Common Name /Local Name | IUCN Status (IUCN, 2012) | Conservation status as per NBFGR-INDIA (Lakra, Sarkar, et al. 2010) |
|---|---|---|---|---|---|
| Cyprinidae | 1 | *Opsarius barna (Hamilton)* | Boroli | LC | – |
| | 2 | *Barilius bendelisis (Hamilton)* | Joia,Guderi | LC | – |
| | 3 | *Barilius barila(Hamilton)* | Chedra | LC | – |
| | 4 | *Barilius vagra(Hamilton)* | korang | LC | – |
| | 5 | *Esomus danrica(Hamilton)* | Flying barb/Danrika | LC | – |
| | 6 | *Crossocheilus latius (Hamilton)* | Stone roller/Lahari,Kalabata | LC | VU |
| | 7 | *Chagunius chagunio (Hamilton)* | Chaguni/Lal puti | LC | EN |
| | 8 | *Danio rerio (Hamilton)* | Zebra danio | LC | – |
| | 9 | *Danio dangila (Hamilton)* | Nipati | LC | VU |
| | 10 | *Devario aequipinnatus (McClelland)* | Giant Danio/Chebli | LC | – |
| | 11 | *Garra gotyla (Gray)* | Sucker head/Budena | LC | VU |
| | 12 | *Garra lamta (Hamilton)* | Lamta Garra | LC | – |
| | 13 | *Garra annandalei(Hora)* | Choak-siGhor-Poia | LC | – |
| | 14 | *Labeo gonius (Hamilton)* | Kuria labeo/Gonya,khursa, Kurchi, Goni | LC | – |
| | 15 | *Neolissochilus hexagonolepis (McClelland)* | Copper mahseer/Bhorkhol, Bulak, Katli | NT | – |
| | 16 | *Neolissochilus hexastichus (McClelland)* | | NT | – |
| | 17 | *Puntius chola (Hamilton)* | Swamp barb | LC | – |
| | 18 | *Pethia conchonius (Hamilton)* | Rosy barb/KanchanPunti | LC | – |
| Balitoridae | 19 | *Balitora brucei (Gray)* | Gray's stone loach/Nau-machee | NT | – |
| Psilorhynchidae | 20 | *Psilorhynchus sucatio (Hamilton)* | River stone carp | LC | – |
| | 21 | *Psilorhynchus balitora (Hamilton)* | Balitora minnow/ Balichura | LC | – |
| Nemacheilidae | 22 | *Acanthocobitis botia (Hamilton)* | Mottled loach/ Bilturi | LC | – |
| | 23 | *Schistura savona (Hamilton)* | Savon khorka | LC | – |
| | 24 | *Schistura multifasciata (Day)* | | LC | VU |
| | 25 | *Schistura devdevi (Hora)* | | NT | – |
| Cobitidae | 26 | *Botia dario (Hamilton)* | Bengal loach/Rani mach,Boumach | LC | VU |
| | 27 | *Lepidocephalichthys guntea (Hamilton)* | Guntea loach/Gutum | LC | – |
| | 28 | *Lepidocephalichthys annandalei (Chaudhuri)* | Annandale loach/Gutum | LC | – |
| Erethistidae | 29 | *Hara horai (Misra)* | Terai hara | LC | – |
| Olyridae | 30 | *Olyra longicaudata (McClelland)* | Bhotsinghi | LC | VU |
| Bagridae | 31 | *Mystus bleekeri (Day)* | Day's mystus/Tengra | LC | – |
| | 32 | *Rita rita (Hamilton)* | Rita/Reti,Reta | LC | – |
| Heteropneustidae | 33 | *Heteropneustes fossilis (Bloch)* | Stinging catfish/Singee,Singhi | LC | VU |
| Sisoridae | 34 | *Glyptothorax indicus (Talwar)* | | LC | – |
| Badidae | 35 | *Badis badis (Hamilton)* | Badis/Bot koi, KaloPunti | LC | VU |
| Channidae | 36 | *Channa orientalis (Bloch& Schneider)* | Walking snakehead/Cheng | NE | – |
| | 37 | *Channa stewartii (Playfair)* | Assamese snakehead | LC | – |
| Gobiidae | 38 | *Glossogobius giuris (Hamilton)* | Tank goby/Balia, Belay | LC | – |
| Mastacembelidae | 39 | *Macrognathus pancalus (Hamilton)* | Barred spiny eel/Baim, Guchi | LC | – |
| | 40 | *Mastacembelus armatus (Lacepède)* | Zig-zag eel/Bami | LC | – |
| Belonidae | 41 | *Xenentodon cancila (Hamilton-Buchanan)* | Freshwater garfish/kakila | LC | – |




(a) (b)

**Fig. 2.** a) Correspondence analysis biplot, explaining the variation in the fish assemblage of River Murti b) Heat map of fish species abundance along with the study sites of River Murti. See species codes in Appendix B.

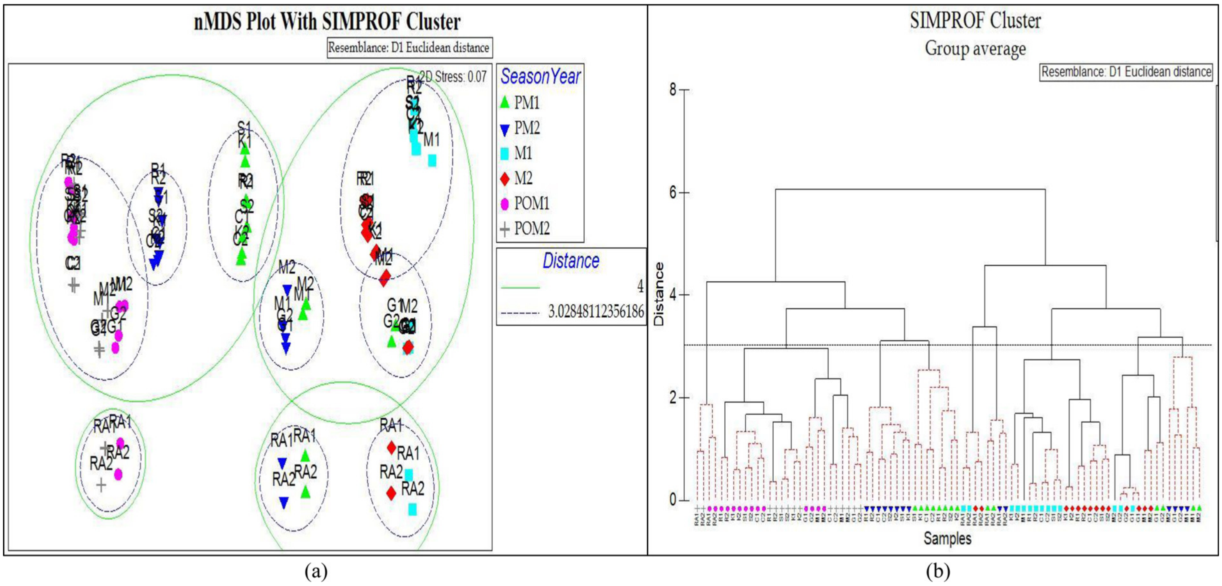



**Fig. 3.** a) Non-metric multidimensional scaling plot (nMDS) projecting Euclidean distance among sites based on environmental distance.(PM: Premonsoon, M: Monsoon, POM: Postmonsoon); b) Clustering of study sites based on similarity profile analysis (SIMPROF) regarding the temporal references in River Murti.

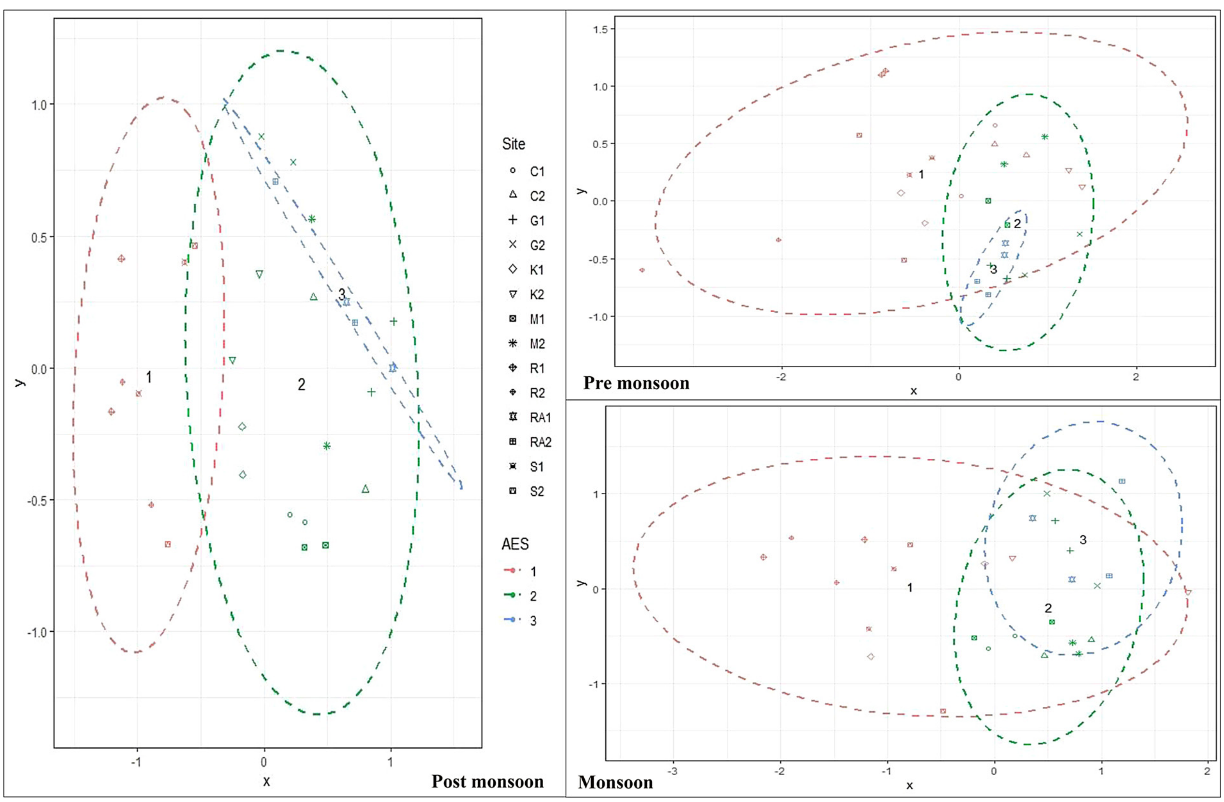



**Fig. 4.** Tri-seasonal variation of fish assemblage among three aquatic ecological systems (AES) of River Murti.

habitat specialist species (Fig.4).

### 3.3. Predictive modelling & evaluation of AES

The RELATE test has elucidated a significant influence of recorded environmental drivers upon species assemblage patterns (Appendix A). Considering both the constrained (11 variables contributing to species assemblage) and unconstrained analysis (12 variables explaining variation in environmental frame) (Appendix A & B), a set of 19 variables (Appendix B) are selected as predictors variables and fitted in the BRT model. In the outputs (Table 3) (Appendix A), the influence of the predictors differs in predicting the responses. Altitude, water hardness, substrate coarseness, and shelter availability broadly impact the species richness, whereas substrate coarseness, water depth, water current, and basin pressure are selected as strong predictors of ichthyofaunal diversity. On another note, the species evenness is mostly modulated by river width, dissolved oxygen, water current, & water depth.

The calculated observed/expected (OE50) ratio has pointed out the number of incidences indicating deviance from the expected scenario considering the threshold-level (Appendix A). Based on the final

**Table 3**
Details of the fitted boosted regression tree (BRT) models upon the three diversity indices, calculated from the ichthyofaunal abundance recorded from the River Murti. (AL: Altitude, SC: Substrate Coarseness, PI: Pressure Index, SH: Shelter Availability, WD: Water Depth, RW: River Width, HA: Water Hardness, WC: Water Current, DO: Dissolved Oxygen).

| Response Variables | Model | Learning Rate | Cross-validation (CV) Fold | Mean CV Deviance | Multiclass ROC of Prediction on Year2 | Top 4 Predictors with highest relative Influence |
|---|---|---|---|---|---|---|
| Shannon Diversity Indices (H’) | BRT with minimum 1000 Trees | 0.01 | 10 | 0.3263549 ± 0.06324754 | 0.9894 | SC<br>WD<br>WC<br>PI |
| Pielou's Evenness(J’) | | 0.003 | 10 | 0.004240468 ± 0.001353714 | 0.9915 | RW<br>DO<br>WD<br>WC |
| Margalef’s Richness (d) | | 0.03 | 10 | 0.004240468 ± 0.001353714 | 0.9892 | AL<br>SH<br>HA<br>SC |

**Table 4**
Checkerboard of transformed observed/expected ratios (O/E) concerning the evaluation of aquatic ecological systems (AES) in River Murti. (PM: Pre Monsoon, M: Monsoon, POM: Post Monsoon).

| AES | Site | Richness | | | Diversity | | | Evenness | | | Total | AES wise Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | PM | M | POM | PM | M | POM | PM | M | POM | | |
| AES1 | R1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 3 | 9 |
| | R2 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 3 | |
| | S1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | S2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | K1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | K2 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 3 | |
| AES2 | C1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| | C2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | M1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | M2 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | |
| | G1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | G2 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 2 | |
| AES3 | RA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | RA2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |

checkerboard-cell value (Table 4) from all the models, it has been presumed that the AES1 has an ‘Impaired’ status indicating 50% or more than 50% loss or temporal deviation in the observed diversity pattern of Year 2. However, AES2 has a ‘With Concern’ status indicating the risk of biodiversity loss or shift in species assemblage pattern, and the rest are in ‘Good’ status. For the impaired AES1, *Neolissochilus hexagonolepis, Neolissochilus hexastichus,* and *Crossocheilus latius* appear to be steno-ranged species which are partly shared by adjacent AES as indicated in the heat map (Fig.2b),. Pearson’s correlation (Fig.5) indicates a positive correlation of basin pressure along with stream order, total dissolved solids (TDS), total alkalinity, and water current. In contrast, a negative correlation is indicated between basin pressure and Qualitat del Bosc de Ribera (QBR) index, substrate coarseness, altitude, shelter availability, distance from Jaldhaka, neutral density vegetation index (NDVI) along with total acidity (Appendix A).

## 4. Discussion

### 4.1. Status of ichthyofaunal diversity

The small-scale torrential Himalayan river, Murti, has a moderate species richness compared to the major rivers viz. Teesta and Jaldhaka, with 92 (Acharjee and Barat, 2013; Chakrabarty and Homechaudhuri, 2013) and 119 (Sarkar and Pal, 2018) identified fish species, respectively. This finding projects to a weak latitudinal gradient in the freshwater fish assemblage from this region, which may have been caused due to the strong effects of local factors controlling the regional species richness (Heino, 2011). However, this study is in agreement with the view that prominent variation in species assemblage occurs along the gradient of altitude, temperature, river morphology and different flow regimes of Himalayan water reaches irrespective of their spatial scale (Acharjee and Barat, 2013; Bhatt et al., 2012; Chakrabarty and Homechaudhuri, 2013). Following the Rapoport's latitudinal rule, a marked reduction has been observed in species richness and diversity with increasing latitude and rising elevation (Bhatt et al., 2012; Stevens, 1992) while anthropogenic stressors might increase the rarity of some fishes in this upland torrential Himalayan river (Mahapatra et al., 2014). Habitat heterogeneity might be the primary driver to allow this diverse scale of species assemblage since it drains different terrains within its course.

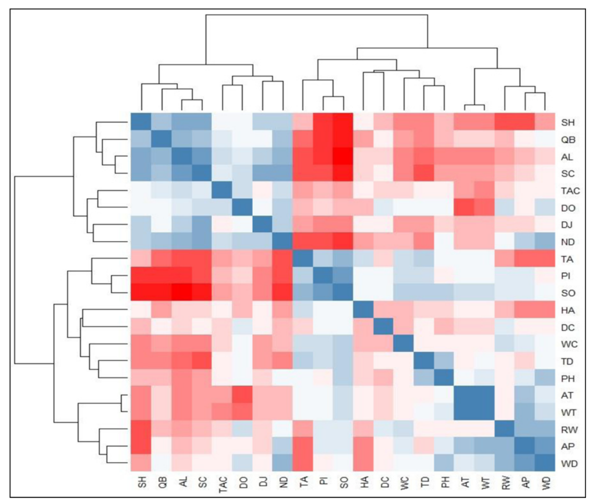



**Fig. 5.** Correlation between the recorded environmental variables of River Murti; Blue indicates positive correlations. Red indicates negative correlations. The darker the color, the stronger the correlation. (WC: Water Current, DO: Dissolved Oxygen, DC: Dissolved $CO_2$, PH: pH, TAC: Total Acidity, TA: Total Alkalinity, HA: Water Hardness, TD: Total Dissolved Solid, ND: Normalized Difference Vegetation Index, QB: Qualitat del Bosc de Ribera (Riparian Forest Quality) Index, SO: Stream Order, AL: Altitude, DJ: Distance from River Jaldhaka, PI: Pressure Index, WD: Water Depth, SC: Substrate Coarseness, RW: River Width, SH: Shelter Availability, AT: Air Temperature, AP: Annual Precipitation, WT: Water Temperature) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

This river is enriched with some of the highly adapted hill stream fishes, which are found along with the Eastern Himalayan biodiversity hotspot (Goswami et al., 2012a). These are namely *Psilorhynchus balitora, Psilorhynchus sucatio, Garra lamta, Garra gotyla gotyla, Garra annandalei,* and *Glyptothorax indicus* out of the 667 species identified from this region (Goswami et al., 2012a). However, they seem to have specific habitat preferences within the water reach, as is evident from the correspondence analysis. This fact increases the conservation value of the AESs of these vast networks of freshwater tributaries. The findings of this study are similar with the projected dominance of cyprinid fishes in most of the freshwater reaches of the Eastern Himalayas (Acharjee and Barat, 2013; Bhatt et al., 2012; Debnath, 2015; Dey et al., 2015a, 2015b; Goswami et al., 2012a; Sarkar and Pal, 2018). As species turnover reflects the sorting of species depending on the environment or dispersal process (Si et al., 2016), a high species turnover trend is observed despite the overlaps between AES groups. It distinctly indicates the sharing of common species along with a few habitat specialists following the gradient. However, low environmental dissimilarity may result in weak species replacement between site R1-R2, G1-G2 & RA 1-RA 2 (Bishop et al., 2015; Hill et al., 2017; Si et al., 2016). Moreover, this investigation has also pointed out 11 significant environmental variables shaping the fish assemblage of River Murti as previously corroborated by Goswami et al., 2012a. These drivers also differ from the vital environmental drivers for large-scale rivers viz—-Teesta from this same eco-region (Bhatt et al., 2012).

As per the models, species evenness is predicted to be more affected by the morphology of this water reach, indicating lower evenness at higher altitudes. Richness and diversity are modulated by substrate coarseness, water hardness, and shelter availability, which are prone to degradation following an increasing trend of anthropogenic pressure, land usages as well as climatic conditions (Heino et al., 2009; Tse-ring et al., 2010). However, the CV correlation value for these models does not cross the threshold, suggesting this inference might have frail information. Moreover, the present findings indicate a significant contribution of the landscape, habitat diversity and riparian influence, playing a pivotal role along with water discharge parameters to shape the species assemblage pattern in these water reaches (Manel et al., 2000; Schlosser, 1991; Weijters et al., 2009; Wiens, 2002), which are in sharp contrast to the species-energy hypothesis (Heino, 2011). In addition to this, these factors are subjected to degradation by direct and indirect effects of changing climate and increasing anthropogenic activities (Heino et al., 2009; Goswami et al., 2012a; Tse-ring et al., 2010).

Following a previous report (Tse-ring et al., 2010), the freshwater riverine ecosystem of this region is vulnerable due to the deposition of sediments, reduced streamflow, disrupted successional stages followed by natural hazards and human-made threats such as pollution, river embankments, sand digging, and construction of hydropower dams (Goswami et al., 2012a). In relation with the findings of this study, these threats might alter the existing environmental filters, acting at both the local and landscape scales inflicting severe concerns towards the ecosystem and biodiversity of the freshwater reaches of Eastern Himalaya (Heino et al., 2009; Goswami et al., 2012a; Tse-ring et al., 2010). As per the shared homology in seasonal flow-hydrography and effect of monsoon among the small-scale tributaries of Dooars region (Mukherjee et al., 2009; Rudra, 2018), this study also indicates a similar role of habitat characteristics and environmental variables, maintaining the existing habitat heterogeneity and species assemblage pattern.

### 4.2. Coarse filter-site prioritization

A top-down classification of AES for River Murti has resulted in three significant AES depending upon its length and size. The number of AES may differ for a large-scale river, as found in the Upper Paraguay River basin (600,000 km$^2$) of Brazil with 102 AESs (Higgins et al., 2005). This finding confirms the presence of a coarse spatial scale, with a discontinuous structure being present in this torrential river. Within this frame, the lateral and vertical geomorphological attributes, as well as environmental similarities, are more relevant to create distinct ecological patches in contrast to longitudinal linkages of rivers in a continuum (Vannote et al., 1980; Poole, 2002). These distinct spatial patches and its ecological process seem to be strongly influenced by the typical landscape of the upland Eastern Himalayan region (Wiens, 2002). Some of the sites are nested with others, and some remain distinct in-spite of temporal perturbation. As observed, sites K1, K2, C1, and C2 lose their characteristics from their corresponding AES during monsoon and consequently show temporal similarity with the closest AES. This situation is presumed to be an impact of a heavy load of water during monsoon, which creates a homogeneous environment. The recorded environmental attributes for AESs are not only found to be significantly associated with the pattern of ichthyofaunal assemblage but would also be relevant for the other aquatic species (Mukherjee et al., 2009; Roy and Homechaudhuri, 2017). The overlap in species assemblage structure describes the spatial and temporal exploitation pattern of the inhabitant fishes following the environmental variation.

As per the comprehensive analysis through evaluation of the O/E ratio (Hermoso et al., 2008; Noss, 2004), the temporal impairment is mostly reflected in the sites of AES1, which indicates shrinkage in fish species availability and distribution. AES1 has distinct species turnover distance with AES2 and AES3, thereby indicating the least chance of species re-colonization through source-sink refilling strategy (Mouquet and Loreau, 2003), when in distress. It also indicates species-filtering at a local scale depending upon characteristic environmental drivers. Thirteen prime variant species belong to this AES of which *Neolissochilus hexagonolepis* (NT), *Neolissochilus hexastichus*(NT), and *Crossocheilus latius* (LC) are restricted to AES1. This fact increases its conservation value when compared to the other AESs. AES1 is presumed to be ranged from an altitude of 482-379 m with the landscape, being mostly dominated by deforested barren lands, tea plantations, and urban build-ups along with intensifying trend of tourism pressure. Therefore, this study stresses the threats of further impairment following a significant shift in the environment, along with the future climatic scenarios and urbanization (Heino et al., 2009; Tiwari et al., 2018). The present study is concerned about the equilibrium of the physical subsystems of these freshwater reaches in terms of ichthyofaunal assemblage to indicate the extent of possible impact at the species level.

## 5. Conclusion

This coarse classification would provide useful information about the variation in functional biotic assemblage within the water reach. As the vast headwaters, small-scale rivers of this region share a prominent homology in physical and environmental attributes, and this study surmises a similar status of aquatic ecological systems regarding piscine diversity in these water reaches. As they are prone to the gradual changes in the environmental frame before other large-scale rivers of the Eastern Himalayan region, this investigation also attempts to predict the cumulative vulnerability of these systems in terms of ecological health and species diversity.

## Ethical approval statement

This study has been conducted following the ethical guidelines endorsed by the University of Calcutta, University Grant Commission, and Govt. of India. No vertebrate animals have been sampled, which are already forbidden to be captured from the wild. No surveys and sampling procedures were extended to the protected areas and the water bodies within. The authors are now declaring the fulfillment of all ethical commitments subjected to this research work.

## Declaration of Competing Interest

The authors are declaring here that no conflict of interest has been raised during the study and published until this report.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.limno.2020.125779.

## References

Acharjee, M., Barat, S., 2013. Ichthyofaunal diversity of Teesta River in Darjeeling Himalaya of West Bengal, India. Asian J. Exp. Biol. Sci. 4 (1), 112–122.
Allen, D.J., Molur, S., Daniel, B.A., 2010. The Status and Distribution of Freshwater Biodiversity in the Eastern Himalaya. IUCN, Cambridge, UK and Gland, Switzerland; Zoo Outreach Organization, Coimbatore, India.
Angermeier, P.L., Karr, J.R., 1983. Fish communities along environmental gradients in a system of tropical streams. Environ. Biol. Fishes 9 (2), 117–135.
Arfanuzzaman, M., 2018. Economics of transboundary water: an evaluation of a glacier and snowpack-dependent river basin of the Hindu Kush Himalayan region. Water Policy 20 (1), 90–108.
Bandyopadhyay, S., Kar, N.S., Das, S., Sen, J., 2014. River systems and water resources of West Bengal: a review. Special Publication of the Geol. Soc. India 3, 63–84.
Baselga, A., Orme, C.D.L., 2012. Betapart: an R package for the study of beta diversity. Methods Ecol. Evol. 3 (5), 808–812.
Beisiegel, Bd.M., 2006. Shelter availability and use by mammals and birds in an Atlantic forest area. Biota Neotrop. 6 (1), 1–16.
Bhatt, J.P., Manish, K., Mehta, R., Pandit, M.K., 2016. Assessing potential conservation and restoration areas of freshwater fish fauna in the Indian river basins. Environ. Manage. 57 (5), 1098–1111.
Bhatt, J.P., Manish, K., Pandit, M.K., 2012. Elevational gradients in fish diversity in the Himalaya: water discharge is the key driver of distribution patterns. PLoS One 7 (9), e46237.
Bishop, T.R., Robertson, M.P., van Rensburg, B.J., Parr, C.L., 2015. Contrasting species and functional beta diversity in montane ant assemblages. J. Biogeogr. 42 (9), 1776–1786.
Bohlin, T., Hamrin, S., Heggberget, T.G., Rasmussen, G., Saltveit, S.J., 1989. Electrofishing—theory and practice with special emphasis on salmonids. Hydrobiologia 173 (1), 9–43.
Borcard, D., Gillet, F., Legendre, P., 2011. Spatial analysis of ecological data. Numerical Ecology With R. Springer, pp. 227–292.
Chakrabarty, M., Homechaudhuri, S., 2013. Fish guild structure along a longitudinally-determined ecological zonation of Teesta, an eastern Himalayan river in West Bengal, India. Arxius de Miscel· lània Zoològica 11, 196–213.
Chakraborty, S., Datta, K., 2013. Causes and consequences of channel changes–a spatio-temporal analysis using remote sensing and GIS—jaldhaka-Diana River System (Lower Course), Jalpaiguri (Duars), West Bengal, India. J. Geogr. Nat. Disasters 3 (1), 1–13.
Chakraborty, S., Mukhopadhyay, S., 2014. A comparative study on the nature of channel confluence dynamics in the lower Jaldhaka River system, West Bengal, India. Int. J. Geol. Earth & Environ. Sci. 4 (2), 87–97.
Chapman, G.P., Rudra, K., 2015. Time streams: history and rivers in Bengal. Centre for Archaeological Studies & Training. Eastern India, pp. 1–45.
Chaudhuri, A., Gangopadhyay, K., Homechaudhuri, S., 2017. Understanding haematopoiesis as survival strategy in two characteristic habitat specialist fishes inhabiting a hill stream environment. J. Environ. Biol. 38 (3), 477.
Chettri, N., Sharma, E., Shakya, B., Thapa, R., Bajracharya, B., Uddin, K., Oli, K.P., Choudhury, D., 2010. Biodiversity in the eastern himalayas: status, trends and vulnerability to climate change. Climate Change Impact and Vulnerability in the Eastern Himalayas—technical Report 2 (p. 7). Kathmandu: International Centre for Integrated Mountain Development (ICIMOD).
Clarke, K., Gorley, R., 2006. PRIMER v6: User Manual PRIMER-E. Plymouth, UK.
Colwell, R.K., Coddington, J.A., 1994. Estimating terrestrial biodiversity through extrapolation. Philos. Trans. R. Soc. Lond., B, Biol. Sci. 345 (1311), 101–118.
Colwell, S., 2007. The Application of the QBR Index to the Riparian Forests of Central Ohio Streams. Ph.D. Thesis. School of Environment and Natural Resources. The Ohio State University p. 44.
Cumming, J., Wooff, D.A., 2007. Dimension reduction via principal variables. Comput. Stat. Data Anal. 52 (1), 550–565.
Debnath, S., 2015. Present status of ichthyofaunal diversity of Gadadhar River at Cooch Behar District, West Bengal, India. Int. J. Pure App. Biosci 3 (5), 42–49.
Dey, A., Nur, R., Sarkar, D., Barat, S., 2015a. Ichthyofauna Diversity of River Kaljani in Cooch Behar District of West Bengal, India. Int. J. Pure App. Biosci 3 (1), 247–256.
Dey, A., Sarkar, K., Barat, S., 2015b. Evaluation of fish biodiversity in rivers of three districts of eastern Himalayan region for conservation and sustainability. IJAR 1 (9), 424–435.
Edwards, E.D., Huryn, A.D., 1996. Effect of riparian land use on contributions of terrestrial invertebrates to streams. Hydrobiologia 337 (1-3), 151–159.
Efird, T.P., Konar, B., 2014. Habitat characteristics can influence fish assemblages in high latitude kelp forests. Environ. Biol. Fishes 97 (11), 1253–1263.
Elith, J., Leathwick, J.R., Hastie, T., 2008. A working guide to boosted regression trees. J. Anim. Ecol. 77 (4), 802–813.
Francis, M.P., Morrison, M.A., Leathwick, J., Walsh, C., 2011. Predicting patterns of richness, occurrence and abundance of small fish in New Zealand estuaries. Mar. Freshw. Res. 62 (11), 1327–1341.
Froese, R., Pauly, D., 2011. FishBase. 2011. World Wide Web electronic publication Available at: http://www/fishbase.org (accessed 22 February 2011).
Goswami, U.C., Basistha, S.K., Bora, D., Shyamkumar, K., Saikia, B., Changsan, K., 2012a. Fish diversity of North East India, inclusive of the Himalayan and Indo Burma biodiversity hotspots zones: a checklist on their taxonomic status, economic importance, geographical distribution, present status and prevailing threats. Int. J. Biodivers. Conserv. 4 (15), 592–613.
Goswami, C., Mukhopadhyay, D., Poddar, B.C., 2012b. Tectonic control on the drainage system in a piedmont region in tectonically active eastern Himalayas. Front. Earth Sci. 6 (1), 29–38.
Guha, D., Bardhan, S., Basir, S.R., De, A.K., Sarkar, A., 2007. Imprints of Himalayan thrust tectonics on the Quaternary piedmont sediments of the Neora–Jaldhaka valley, Darjeeling–Sikkim Sub-Himalayas, India. J. Asian Earth Sci. 30 (3–4), 464–473.
Hauer, F.R., Lamberti, G. (Eds.), 2011. “Methods in Stream Ecology.”. Academic Press, pp. 4–141.
Heino, J., 2011. A macroecological perspective of diversity patterns in the freshwater realm. Freshw. Biol. 56 (9), 1703–1722.
Heino, J., Virkkala, R., Toivonen, H., 2009. Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions. Biol. Rev. 84 (1), 39–54.
Hermoso, V., Blanco-Garrido, F., Prenda, J., 2008. Spatial distribution of exotic fish species in the Guadiana river basin, with two new records. Limnetica 27 (1), 189–194.
Hermoso, V., Linke, S., Prenda, J., 2009. Identifying priority sites for the conservation of freshwater fish biodiversity in a Mediterranean basin with a high degree of threatened endemics. Hydrobiologia 623 (1), 127–140.
Higgins, J.V., Bryer, M.T., Khoury, M.L., Fitzhugh, T.W., 2005. A freshwater classification approach for biodiversity conservation planning. Conserv. Biol. 19 (2), 432–445.
Hill, M.J., Heino, J., Thornhill, I., Ryves, D.B., Wood, P.J., 2017. Effects of dispersal mode on the environmental and spatial correlates of nestedness and species turnover in pond communities. Oikos 126 (11), 1575–1585.
IUCN, S., 2012. IUCN Red List of Threatened Species." International Union for Conservation of Nature 2011.
Jayaram, K., Singh, K., 1977. On a collection of fish from North Bengal. Rec. Zool. Surv. India 72 (1–4), 243–275.
Jolliffe, I., 2003. Principal component analysis. Technometrics 45 (3), 276.
Kapoor, M., Kohli, K., Menon, M., 2009. India’s notified ecologically sensitive areas (ESAs): the story so far. Kalpavriksh 82–83.
Kar, R., Chakraborty, T., Chakraborty, C., Ghosh, P., Tyagi, A.K., Singhvi, A.K., 2014. Morpho-sedimentary characteristics of the Quaternary Matiali fan and associated river terraces, Jalpaiguri, India: implications for climatic controls. Geomorphology 227, 137–152.
Khoury, M., Higgins, J., Weitzell, R., 2011. A freshwater conservation assessment of the Upper Mississippi River basin using a coarse-and fine-filter approach. Freshw. Biol. 56 (1), 162–179.
Kindt, R., Coe, R., 2005. Tree Diversity Analysis: a Manual and Software for Common Statistical Methods for Ecological and Biodiversity Studies. World Agroforestry Centre, pp. 1–70.
Kindt, R., Kindt, M.R., 2018. Package ‘BiodiversityR’, Obtenido De. http://vps. fmvz. usp. br/CRAN/web/packages/BiodiversityR/BiodiversityR. pdf. .
Kundu, S., Rath, S., Laishram, K., Pakrashi, A., Das, U., Tyagi, K., Kumar, V., Chandra, K., 2019. DNA barcoding identified selected ornamental fishes in Murti river of East India. Mitochondrial Dna Part B 4 (1), 594–598.
Lakra, W.S., Sarkar, U., Gopalakrishnan, A., Kathirvelpandian, A., 2010. Threatened freshwater fishes of India. National Bureau of Fish Genetic Resources. NBFGR Publication, pp. 11–18.
Linke, S., Norris, R., 2003. Biodiversity: bridging the gap between condition and conservation. Aquatic Biodiversity. Springer, pp. 203–211.
Mahapatra, B.K., Sarkar, U.K., Lakra, W.S., 2014. A Review on status, potentials, threats and challenges of the fish biodiversity of West Bengal. J. Biodivers. Bioprospect. Dev. 2 (140) 2376-0214.
Manel, S., Buckton, S., Ormerod, S., 2000. Testing large-scale hypotheses using surveys: the effects of land use on the habitats, invertebrates and birds of Himalayan rivers. J. Appl. Ecol. 37 (5), 756–770.
McRae, L., Deinet, S., Freeman, R., 2017. The diversity-weighted living planet index: controlling for taxonomic bias in a global biodiversity indicator. PLoS One 12 (1),

e0169156.
Mouquet, N., Loreau, M., 2003. Community patterns in source-sink metacommunities. Am. Nat. 162 (5), 544–557.
Mukherjee, A., Fryar, A.E., Thomas, W.A., 2009. Geologic, geomorphic and hydrologic framework and evolution of the Bengal basin, India and Bangladesh. J. Asian Earth Sci. 34 (3), 227–244.
Mukhopadhyay, T., Bhattacharjee, S., 2018. Analyses of genetic diversity of Badis badis (Hamilton-Buchanan 1822) from three Riverine systems in sub-Himalayan biodiversity hotspot of west Bengal, India using RAPD and ISSR fingerprinting. Genetika 50 (3), 771–790.
Mukhopadhyay, T., Bhattacharjee, S., 2019. Genetic diversity and population structure analyses of threatened Amblyceps mangois from Sub-Himalayan West Bengal, India through rapd and ISSR fingerprinting. Croat. J. Fish. 77 (1), 33–50.
Noss, R.F., 2004. Conservation targets and information needs for regional conservation planning. Nat. Areas J. 24 (3), 223–231.
Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'hara, R., Simpson, G.L., Solymos, P., Stevens, M.H.H., Wagner, H., 2013. Package 'vegan'. Community ecology package, version 2 (9), 1–295.
Paliy, O., Shankar, V., 2016. Application of multivariate statistical techniques in microbial ecology. Mol. Ecol. 25 (5), 1032–1057.
Patra, B.C., Kar, A., Bhattacharya, M., Parua, S., Shit, P.K., 2017. Freshwater fish resource mapping and conservation strategies of West Bengal, India. Spat. Inf. Res. 25 (5), 635–645.
Pettorelli, N., Ryan, S., Mueller, T., Bunnefeld, N., Jędrzejewska, B., Lima, M., Kausrud, K., 2011. The Normalized Difference Vegetation Index (NDVI): unforeseen successes in animal ecology. Clim. Res. 46 (1), 15–27.
Poiani, K.A., Richter, B.D., Anderson, M.G., Richter, H.E., 2000. Biodiversity conservation at multiple scales: functional sites, landscapes, and networks. Aibs Bull. 50 (2), 133–146.
Poole, G.C., 2002. Fluvial landscape ecology: addressing uniqueness within the river discontinuum. Freshw. Biol. 47 (4), 641–660.
Roy, A., Homechaudhuri, S., 2017. Comparing diversity of freshwater macroinvertebrate community along habitat gradients within a riverine system in North Bengal. J. Entomol. Zool. Stud. 5 (4), 86–93.
Rudra, D.K., 2016. State of India's river. India River Week- West Bengal. SANDRP Publications 2017 (3), 1–6.
Rudra, K., 2014. Changing river courses in the western part of the Ganga–Brahmaputra delta. Geomorphology 227, 87–100.
Rudra, K., 2018. Rivers of the Tarai–Doors and barind tract. Rivers of the Ganga-Brahmaputra-Meghna Delta. Geography of the Physical Environment. Springer, pp. 27–47.
Sarkar, T., Pal, J., 2018. Diversity and conservation status of Ichthyofauna in the river Jaldhaka, West Bengal. Int. J. Fisheries and Aquatic Studies 6, 339–345.
Schlosser, I.J., 1991. Stream fish ecology: a landscape perspective. BioScience 41 (10), 704–712.
Si, X., Baselga, A., Leprieur, F., Song, X., Ding, P., 2016. Selective extinction drives taxonomic and functional alpha and beta diversities in island bird assemblages. J. Anim. Ecol. 85 (2), 409–418.
Singh, R.B., 2015. Urban development challenges, risks and resilience in Asian mega cities. Advances in Geographical and Environmental Sciences. Springer, Tokyo, pp. 31–223.
Skovgaard, L.T., 2000. Applied regression analysis. 3rd edn. NR Draper and H. Smith, Wiley, New York, 1998. No. Of pages: xvii + 706. Price:£ 45. ISBN 0-471-17082-8. Stat. Med. 19 (22), 3136–3139.
Stevens, G.C., 1992. The elevational gradient in altitudinal range: an extension of Rapport's latitudinal rule to altitude. Am. Nat. 140 (6), 893–911.
Talwar, P., Jhingran, A., 1991. Inland Fishes of India and Adjacent Countries. 2 Vols. Oxford&IBH Publishing Co., New Delhi, Bombay, Calcutta.
Team, R., 2015. RStudio: Integrated Development for R. RStudio, Inc., Boston, MA URL http://www. rstudio. com 42.
Team, R.C., 2018. R: a Language and Environment for Statistical Computing. Available online at. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.
Ter Braak, C.J., 1986. Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis. Ecology 67 (5), 1167–1179.
Tiwari, P.C., Tiwari, A., Joshi, B., 2018. Urban growth in Himalaya: understanding the process and options for sustainable development. J. Urban and Regional Studies on Contemporary India 4 (2), 15–27.
Torondel, B., Ensink, J.H., Gundogdu, O., Ijaz, U.Z., Parkhill, J., Abdelahi, F., Nguyen, V.A., Sudgen, S., Gibson, W., Walker, A.W., 2016. Assessment of the influence of intrinsic environmental and geographical factors on the bacterial ecology of pit latrines. Microb. Biotechnol. 9 (2), 209–223.
Tse-ring, K., Sharma, E., Chettri, N., Shrestha, A.B., 2010. Climate change vulnerability of mountain ecosystems in the Eastern Himalayas. Int. centre for integrated mountain Dev (ICIMOD).
Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37 (1), 130–137.
Weijters, M.J., Janse, J.H., Alkemade, R., Verhoeven, J., 2009. Quantifying the effect of catchment land use and water nutrient concentrations on freshwater river and stream biodiversity. Aquat. Conserv. Mar. Freshw. Ecosyst. 19 (1), 104–112.
Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. J. Geol. 30 (5), 377–392.
Wiens, J.A., 2002. Riverine landscapes: taking landscape ecology into the water. Freshw. Biol. 47 (4), 501–515.