Understanding the impact of future climatic scenarios upon key environmental factors that determine piscine assemblage of a torrential upland river of Eastern Himalayas, India

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Small-scale freshwater reaches would be affected prior to changing climatic scenarios in the coming days. This study aims to build a profile of climate-change impact for the key environmental factors related to the fish assemblage of a small-scale upland river (Murti) in the Eastern Himalayas, India. In the coming future, climate change will lead to increased water current, acidity, pH, riparian quality and NDVI for this freshwater reach. At the same time, decreasing trend of shelter availability and substrate coarseness are projected from the same. River width seems to be less affected, but the whole watershed will experience loss of spatial heterogeneity with regard to these factors.

Keywords: Climate change, Eastern Himalayas, torrential river, piscine assemblage, environmental factors.

IMPACTS of climate change have been a global concern in this present decade[1,2]. Although climate has never been static[3,4], the degradation of natural systems is accelerated due to increased human footprints coupled with changing climatic conditions[5,6]. According to some reports, both the terrestrial and aquatic environments would face grave danger following the recent trends of climate change scenarios[7,8]. Among the aquatic systems, freshwater habitats constitute 1% of the total earth surface area increasing vulnerability to the climate change impacts[9].

Among the freshwater systems, streams and rivers are prone to be affected by future climatic conditions[10,11]. Temperature and precipitation grossly characterize the climatic conditions of streams and rivers, influencing biotic and abiotic interactions in significant measures[10,12]. Freshwater fishes have been subjected to numerous studies for their responses and vulnerabilities to the recent trends of climatic conditions[11–13]. These studies indicate that climate change might modulate the distribution, interactions and ecology of fishes in a complicated manner along with their rate of exploitation and habitat degradation[14,15].

The Eastern Himalayas (EH), India, has a vast network of freshwater tributaries with exclusive species diversity. According to IUCN[16], 1073 taxa inhabit these waters while piscine diversity dominates with about 520 taxa. In the context of EH[17], annual air temperature is reported to be gradually rising[18]. As per the Fifth Assessment Report[19], there will be an average of 2°–3°C (6°C in high latitudes) rise in annual mean temperature over the Asian land masses and Tibetan Plateau at the end of the 21st century. As the Himalayan glaciers support these freshwater reaches, warming would have an impact upon both the biotic and abiotic attributes of rivers and streams[17,18,20]. The Upper Brahmaputra (UB) basin of EH harbours a vast ichthyofaunal diversity[21,22], which is projected with the highest vulnerability index of climate change[18,20]. However, fine-scale simulation of predicted climate scenario upon the small-scale torrential reaches is lacking. Therefore, this study aims to understand the effect of future climatic conditions on the abiotic factors associated exclusively with the piscine diversity of a representative torrential river, viz. River Murti of the UB basin. The projections are made based on current and two future scenarios, i.e. 2050 and 2070.

Materials and methods

Study area

River Murti originates from the MO forest located within the Neora Valley National Park in EH[23]. It traverses 47.5 km before confluence with a sizeable Himalayan river, viz. the Jaldhaka near Gorumara National Park[23]. Seven sites (7–10 km apart), considering a riffle and pool along the altitudinal gradients, were selected for sampling (Figure 1).

Stream watershed delineation

Elevation data (digital elevation model) were obtained from the HydroSHEDS platform (https://www.hydrosheds.org/) at 30 arcsec resolution along with polyline stream

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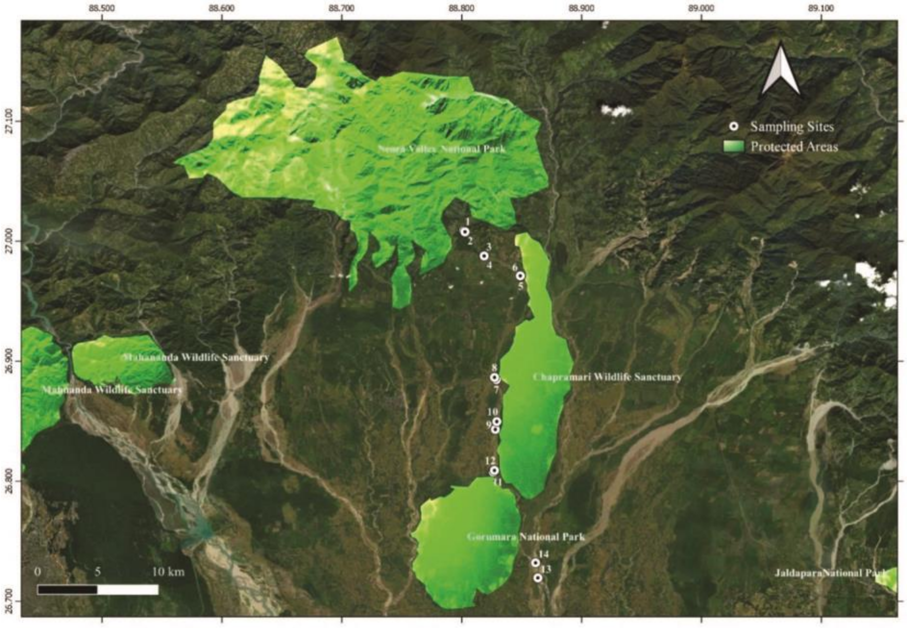

Figure 1. Study area in River Murti, Eastern Himalayas, India.

networks for the study area[24]. The watershed area for River Murti was delineated in Arc GIS (10.2.2) and separated from the River Jaldhaka at the level of their confluence.

Extrapolation of climatic data

Gridded bioclimatic variables at 30 arcsec derived from temperature and precipitation (monthly) were used in the climatic modelling[25]. Among the 19 statistically downscaled bioclimatic variables, annual mean temperature, temperature seasonality, maximum temperature of the warmest month, minimum temperature of the coldest month, mean temperature of the warmest quarter, mean temperature of the coldest quarter, annual precipitation, precipitation of the wettest month and precipitation of the driest month, precipitation seasonality, precipitation of wettest quarter, precipitation of driest quarter were selected based on their relevance to freshwater hydrological regimes[26]. Therefore, current climatic conditions were obtained as scenarios data representative of 1960–1990 (ref. 25). The ensembled future scenarios were obtained from downscaled global climate model (GCM) data from CMIP5 (IPPC fifth assessment) for 2050 and 2070 (ref. 25) considering two scenarios of radiative forcing, i.e. representative concentration pathways (RCPs) 4.5 and 8.5 (ref. 27). RCP 4.5 addresses the global emission of greenhouse gases (GHGs) and land-use-land-cover changes in the global economic framework[28]. On the other hand, RCP 8.5 addresses the highest emission of GHGs and considers high population growth in the absence of any climate-change policies[27]. These scenarios were obtained from WorldClim 1.4 (http://worldclim.org/version1), viz. current, RCP4.5_2050, RCP4.5_2070, RCP8.5_2050 and RCP8.5_2070 (refs 25, 28).

Sampling

The study was conducted from April 2016 to 2018 during three seasons, viz. pre-monsoon, monsoon and post-monsoon.

Environmental data: Environmental variables were recorded to analyse five significant characteristics such as water quality, climate profile, habitat diversity, landscape features and basin pressure of this river, considering area, ecosystem and species-specific attributes (Table 1)[21,23].

Ichthyofaunal data: Fish abundance was recorded by single-pass electrofishing (1020 NP Ultrasonic Inverter Electro Fisher), followed by a current net (mesh size 2.5×2.5 cm). The removal method of estimation was used, and consecutively three efforts were applied for each sampling attempt for a total length of 90 m (ref. 29). All the immobilized fishes were identified up to species level, according to Talwar and Jhingran[30] and FishBase (www.fishbase.org)[31].

Data analysis

A primary square-root transformation was applied to species abundance data, whereas a log transformation was applied to environmental variables[32]. The statistical

Table 1. Environmental variables recorded from River Murti, Eastern Himalaya, India

Variable class	Recorded variables	Standard protocol/kit	Mean
	Water current (m s^{-1})	Propeller-type water current meter (Lawrence & Mayo)	0.31 ± 0.26
	Dissolved oxygen (mg l^{-1})	Water Ecology kit, Hach Model AL-36B kit 180202	11.30 ± 2.79
Water quality	Dissolved CO_2 (mg l^{-1})	Same	8.45 ± 3.63
	pH	Same	8.06 ± 0.87
	Total acidity (mg l^{-1})	Same	3.61 ± 2.96
	Total alkalinity (mg l^{-1})	Same	19.21 ± 12.76
	Water hardness (mg l^{-1})	Same	25.84 ± 8.59
	TDS (mg l^{-1})	OAKTON Multiparameter PCSTestr 35	30.85 ± 7.98
Landscape features	NDVI	ISRO-Bhuvan Database (1 : 320,000) (https://bhuvan.nrsc.gov.in/bhuvan_links.php)	0.48 ± 0.12
	QBR index	Following Colwell *et al.*[59]	62.14 ± 24.98
	Stream order	Hydrology map (1 : 66,667)	4.42 ± 0.49
	Altitude (m)	Garmin eTrex GPS	244.10 ± 141.76
	Distance from Jaldhaka (m)	Garmin eTrex GPS	4394.85 ± 2082.03
Basin pressure	Basin pressure index	Following Hermoso *et al.*[60]	9.67 ± 4.18
	Water depth (m)	Measuring rod and tapes	1.82 ± 1.67
Habitat diversity	Substrate coarseness	Following Wentworth method	10.60 ± 5.31
	River width (m)	Measuring rod and tapes	16.19 ± 7.50
	Shelter availability (sq. km)	Following Beisiegel *et al.*[61]	0.15 ± 0.12
	Air temperature (°C)	OAKTON Multiparameter PCSTestr 35	25.33 ± 6.361
Climate profiles	Annual precipitation (mm)	Indian Meteorological Survey data (www.imd.gov.in/pages/services_hydromet.php)	288.57 ± 374.64
	Water temperature (°C)	OAKTON Multiparameter PCSTestr 35	22.99 ± 5.88

*QBR Index, Qualitat del bosc de ribera; NDVI, Normalized difference vegetation index; TDS, Total dissolved solid.

analysis for this study was performed in PRIMER-E V6.1.18 (https://www.primer-e.com/)[32] and R platform (http://www.rstudio.com)[33].

Filtering environmental variables: A bio-environment statistical relationship test (BIO ENV) was conducted using the recorded species abundance and environmental variables[34]. The best-explained variables to resultant species assemblage were plotted in a non-metric multidimensional (nMDS) plot. This indicates the variability of key factors responsible for the resultant piscine diversity. These variables were filtered from 21 recorded variables and logically projected against the climate-change scenarios upon River Murti.

Modelling impact of future climatic scenarios: Since the fine-scale spatial data for all the recorded environmental variables were not available, a thorough simulation was done using only relevant factors as dummies to determine the fate of piscine diversity over future climatic scenarios. The boosted regression model was fitted upon the pooled value for each of the filtered environmental variables spatially with current climatic conditions. Later, prediction was made based on the best trees upon four future scenarios, viz. RCP4.5_2050, RCP4.5_2070, RCP8.5_2050 and RCP8.5_2070. The learning rate for each set of regression models was kept low, with ten-fold cross-validation[35]. The outputs were clipped based on the spatial frame of the Murti river watershed to visualize the four future climatic scenarios.

Results

Key environmental variables

A total of 41 fish species were identified from this river, of which 4 species belonged to the IUCN Red List Categories[31,36] (Supplementary Table 1). From the BIO-ENV analysis, ten environmental variables explain the current pattern of species assemblage at best (Figure 2). They are water current, pH, total acidity, water hardness, qualitat del bosc de ribera (QBR) index, normalized difference vegetation index (NDVI), altitude, substrate coarseness, shelter availability and river width. Since climatic factors will not influence altitude, the rest of the nine variables have been selected for the future climate-change scenarios.

From the trajectorially projected association, it is prominent that the variability of water current influences *Puntius chola*, *Labeo gonius*, *Lepidocephalichthys guntea*, *Lepidocephalichthys annandalei*, *Glossogobius giuris*, *Chagunius chagunio* and *Opsarius barna* (Figure 2). The assemblage pattern of *L. guntea*, *C. chagunio*, *O. barna* and *Macrognathus pancalus* are also reliant upon the pH of water. *Neolissochilus hexagonolepis*, *Neolissochilus hexastichus*, *Devario aequipinnatus*, *Garra lamta*, *Garra annandalei* and *Crossocheilus latius* strictly follow the altitudinal variation followed by QBR index and acidity of water. *Badis badis*, *Balitora brucei*, *Schistura multifasciata* and *Danio dangila* also have a

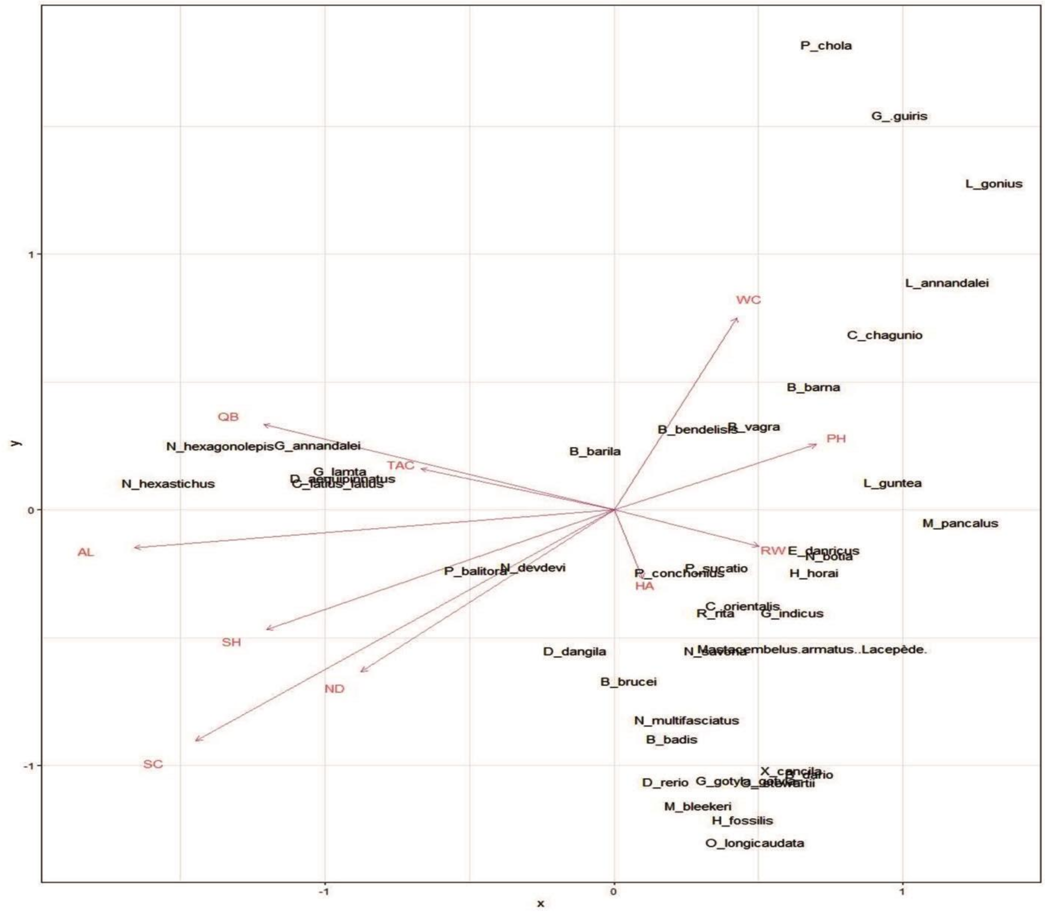

Figure 2. Non-metric multidimensional plot of BIO ENV analysis regarding piscine assemblage of River Murti.

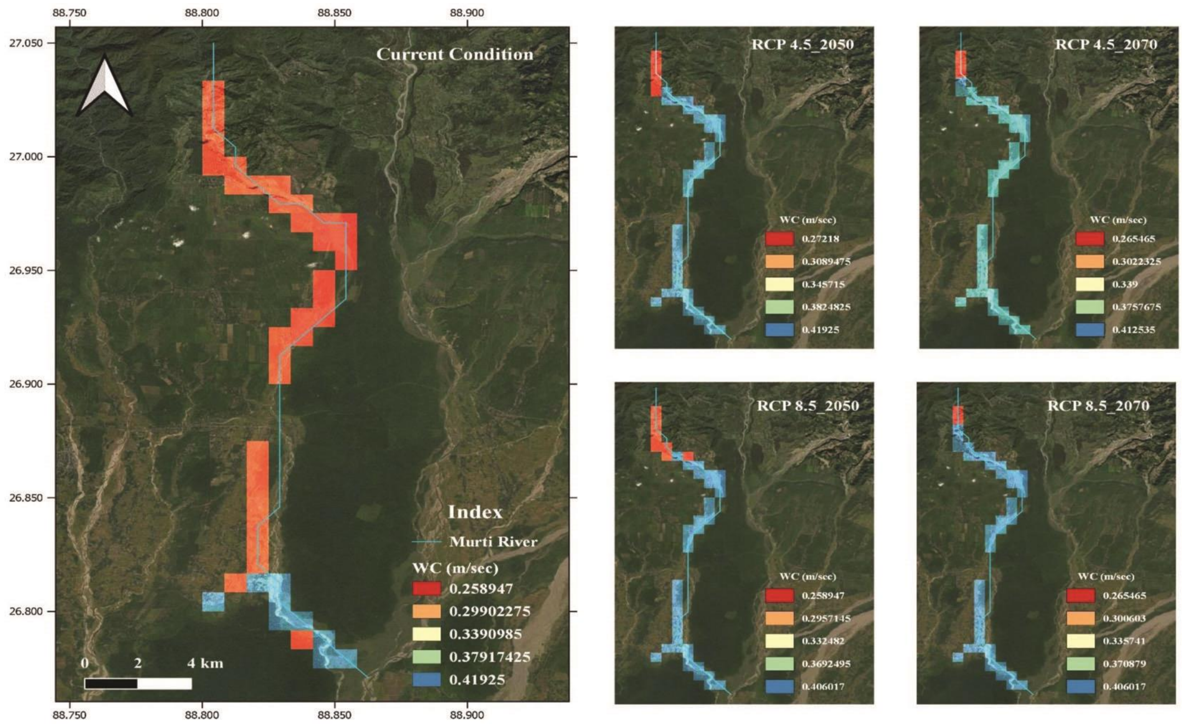

Figure 3. Water current scenarios for the near and distant future in River Murti.

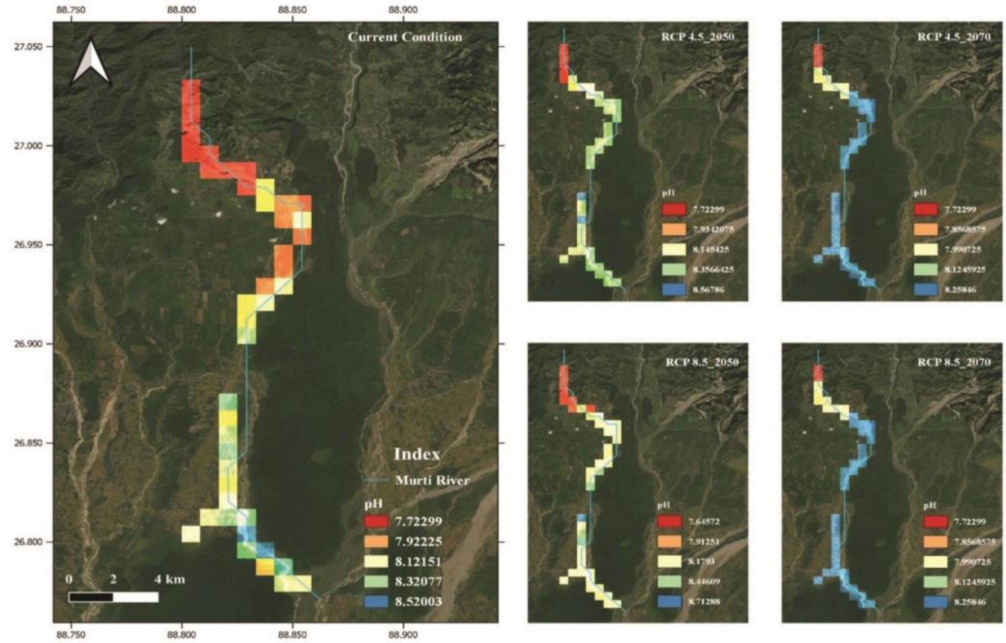

Figure 4. Water pH scenarios for the near and distant future in River Murti.

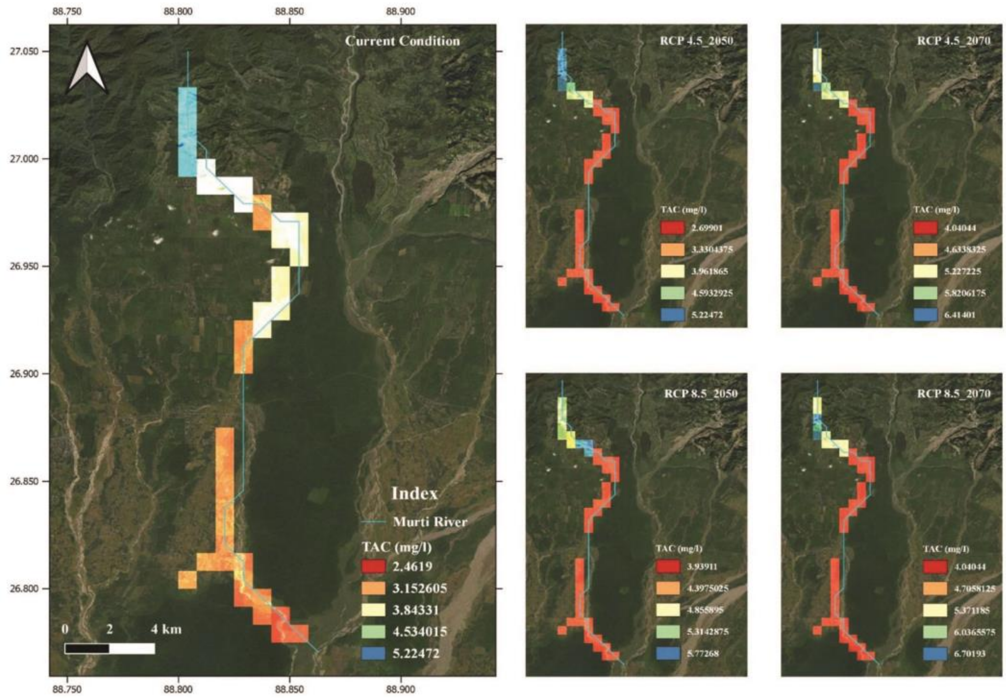

Figure 5. Total acidity scenarios for the near and distant future in River Murti.

contingent association with NDVI of the watershed. However, river width and water hardness seem to explain the pattern of species assemblage less.

Impact of climatic scenarios

The predicted scenarios for RCP4.5_2050, RCP4.5_2070, RCP8.5_2050 and RCP8.5_2070 from the current scenarios were separately projected. Since there has been a lack of fidelity with the fitted model of water, hardness was excluded from the projection.

Water current: In the current spatial projection, water current seems to be higher in the lower plains while the rest of the watershed area has low to moderate values of the same (Figure 3). In 2050, increased water current is

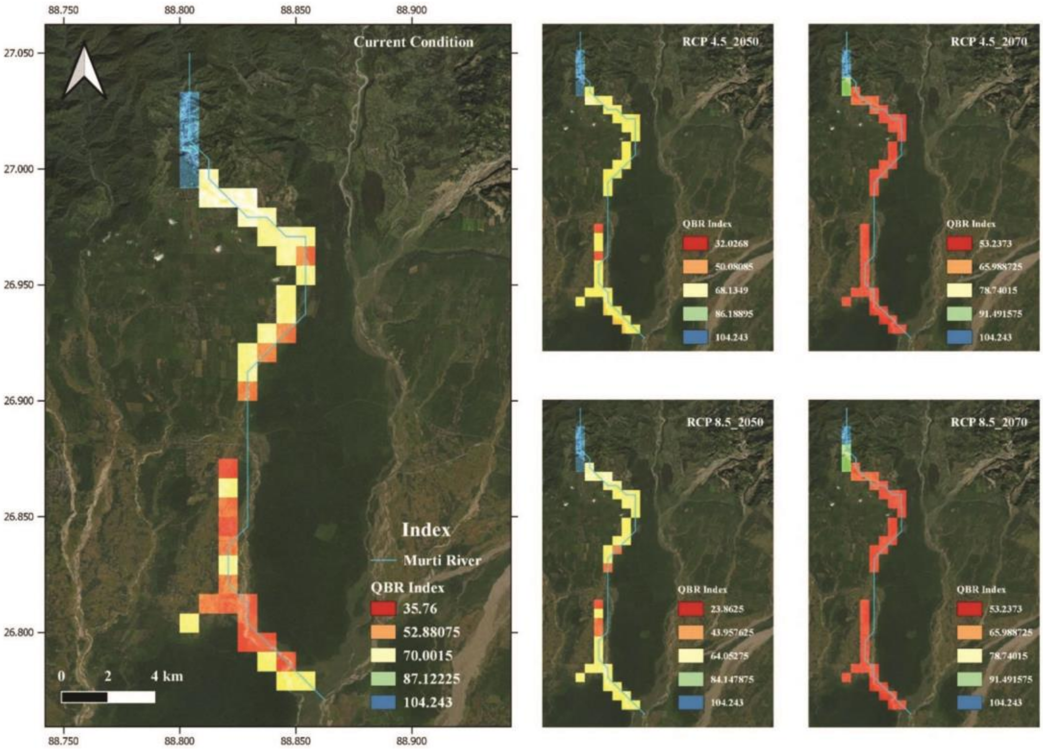

Figure 6. Qualitat del bosc de ribera (QBR) index scenarios for the near and distant future in River Murti.

projected throughout the river watershed, except for the headwaters. However, water current has increased for the higher elevation areas compared to current climatic conditions. A slight spatial variation is also projected in the RCP8.5_2050 scenario. In future 2070 scenarios, the projection remains similar, except the loss variation is extended towards the headwaters more in both RCP 4.5 and 8.5 scenarios.

pH: Acidification is indicated in the upstream of the river in 2050 compared to the current conditions (Figure 4). However, the lower part of the watershed seems to have increasing pH, indicating an increase in the alkalinity in the waters. In 2070, the whole watershed has a weak drop in pH compared to the current conditions, except for the headwaters. However, the signature of spatial variation shows a decrease.

Total acidity: The total acidity of the water seems to increase compared to the current climatic conditions in the high altitudinal areas, along with the four climatic scenarios (Figure 5). RCP 8.5 projects comparatively higher values of acidification in the waters. The rest of the areas of the watershed would experience a moderate homogenous increase in both scenarios.

QBR index: This index fundamentally indicates the quality of riparian vegetation and contribution to the watershed. In the current climatic conditions, higher values are observed around the headwaters (Figure 6). However, in future projections of 2050, the values increase in both the RCP models, but decrease in 2070. Headwaters seem to be unaffected in future scenarios.

NDVI: This would decrease in 2050 along the watershed except for the headwaters, but the spatial variation seems to be higher in the RCP 8.5 scenario (Figure 7). In 2070, the values are similar compared to the current climatic conditions. However, the signature of spatial variation is lost.

Substrate coarseness: In the four future projections, substrate coarseness seems to decrease along with spatial variation (Figure 8). The coarseness of headwater–substratum also seems to be affected in distant future scenarios, indicating a trend of siltation in this water reach.

Shelter availability: According to the results, the availability of in-stream shelter might decrease, except for the headwaters in future scenarios (Figure 9). The spatial variations seem to be lost along the watershed.

River width: In the current climatic condition, a prominent spatial variation has been projected with regard to river width (Figure 10). In RCP4.5_2050 scenario, river width is decreased compared to the current scenario, while it is increased in RCP8.5_2050. In both the future

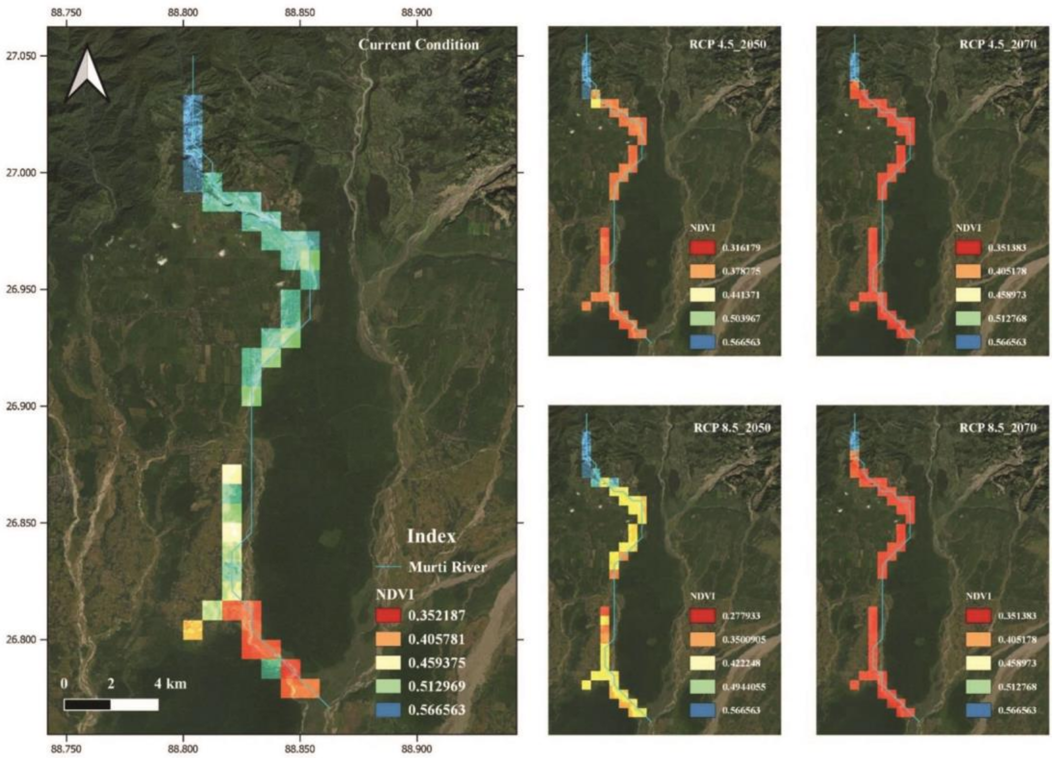

Figure 7. Normalized difference vegetation index scenarios for the near and distant future in River Murti.

projections of 2070, river width does not show much difference; yet it might lose spatial variation.

Discussion

Large freshwater rivers would get more chance to restore ecological processes and support the inhabiting species, while small-scale rivers would be impacted at a faster rate by climate change[37,38]. Fishes are subjected to ecological stresses and pathogens along with climate-induced extremities[38]. These findings mainly focus on small-scale reaches and stress upon the loss of heterogeneity, rather than extremities of the environmental frame predicted by the projected climate change.

Key environmental drivers of the small-scale torrential river

The findings of this study indicating vital environmental factors modulating fish assemblage differ from other studies[21,39,40] due to the scale of such freshwater reaches. For a large river like the Teesta[41], the ichthyofaunal assemblage pattern is driven by water discharge, temperature and phytoplankton[21]. Nevertheless, water discharge parameters and temperature are the secondary modulators for this small-scale upland river of EH. According to previous studies, temperature is the significant determinant of stream fish assemblages[42,43]. However, exceptions are reported[44], as fishes are suitable adaptors and behavioural thermoregulators[44,45]. In the present study, the primary modulators are water quality, habitat diversity and landscape features, which are prone to be degraded by the changing climatic conditions[17,18,20,46]. However, climate would indirectly affect these components[11,47] depending on the catchment scenarios[18,20,37].

Future scenarios of key environmental drivers

Despite using different models, the outputs have not produced many variations. In the near future, increased water current, variability in pH, riparian quality and NDVI might have resulted from increased annual precipitation[48,49] and temperature[10,11,37], as predicted over the EH[20]. Increased riparian quality might impose a positive effect on the hydro-ecology[50–52]. In contrast, water load might increase in the lower plains following the broader catchment area compared to the headwaters[24,53].

In the distant future, decreasing pH and increasing acidity of water might be coupled with increasing organic inputs, pollution and climatic modulation[37]. Decreasing riparian quality and NDVI might degrade these freshwater reaches. However, increased precipitation and water load in the future would not affect the river width, as these water reaches contain large alluvial and para

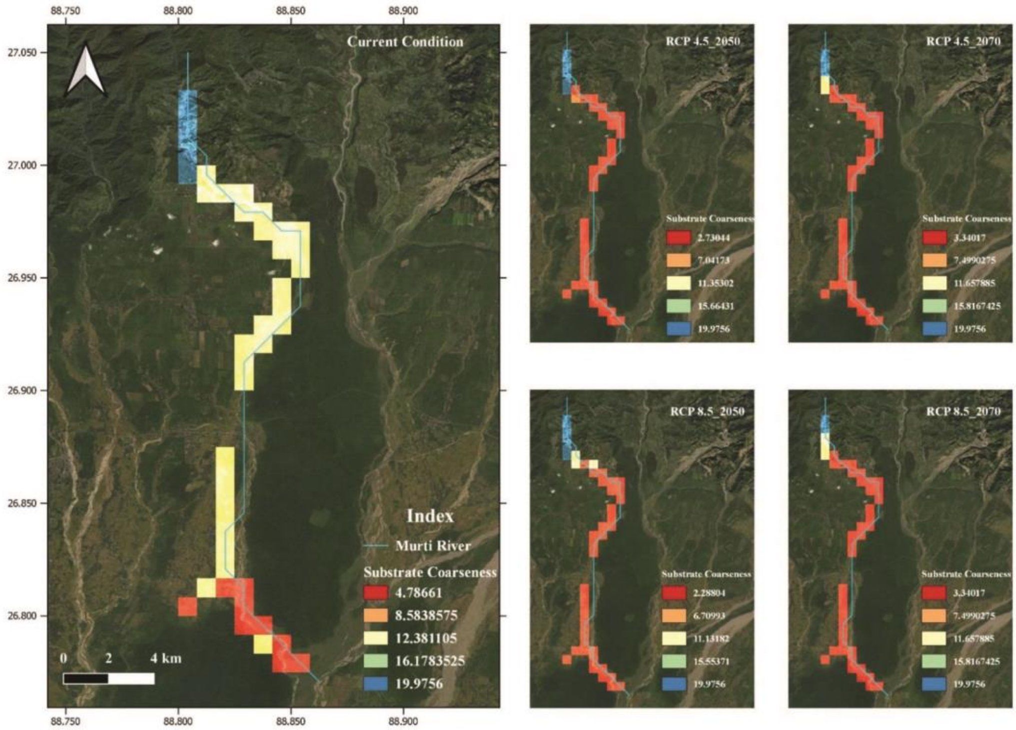

Figure 8. Substrate coarseness scenarios for the near and distant future in River Murti.

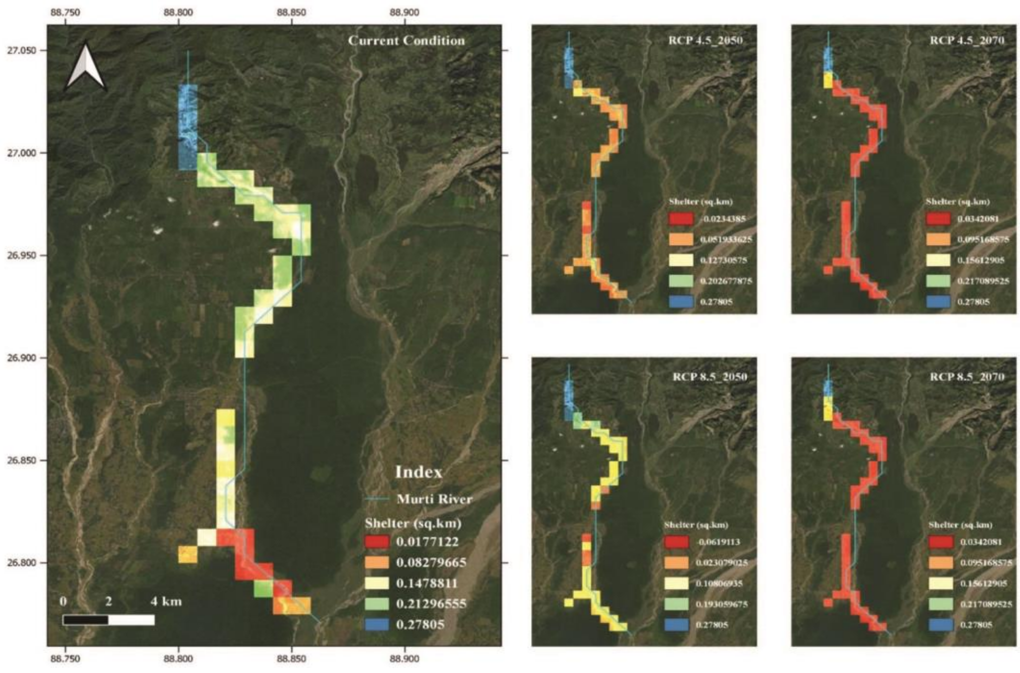

Figure 9. Shelter availability scenarios for the near and distant future in River Murti.

fluvial zones to accommodate the lateral flow of water[53,54].

Warming across the EH[20] would increase the rate of snow melting affecting the downstream regions[17,18,55,56]. The present finding indicates a similar impact on water current of this freshwater reach in agreement with previous works[10,17,18,37]. Previous studies depict that a warmer and wetter climate may accelerate acidification by modulating nitrogenous and organic release in water[11,57]. Nutrients of water are interlinked with substrate and soil as they are released in the water through water current, volume and dilution[37]. Therefore, alteration in

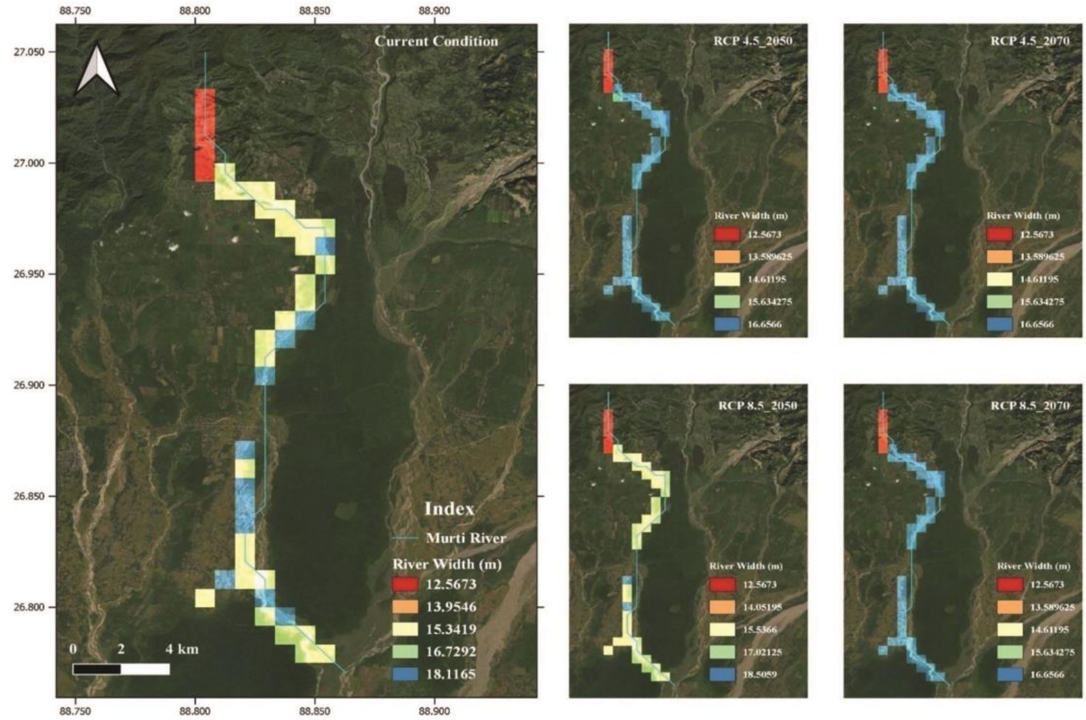

Figure 10. River width scenarios for the near and distant future in River Murti.

these critical factors would affect the productivity of the water and planktonic richness while leading to higher eutrophication[11,20,57,58]. Despite having temporal variability in the future environmental frame, spatial variability will be lost for this freshwater reach.

Impact upon ichthyofaunal assemblages

With increasing water current and decreasing spatial variation, the distribution and adaptability of fishes like *P. chola*, *L. gonius*, *L. guntea*, *L. annandalei*, *G. giuris*, *C. chagunio* and *O. barna* may be a challenge (Figure 2). Following the similar trend of acidification and loss of spatial variation in future, the distribution of high-altitude resident species, namely *N. hexagonolepis*, *N. hexastichus*, *D. aequipinnatus*, *G. lamta*, *G. annandalei* and *C. latius* will be subjected to vulnerability. Following pH and acidification, *L. guntea*, *C. chagunio*, *O. barna* and *M. pancalus* may experience habitat expansion in this river. However, the suitable riparian cover might elevate the organic constitution, benefitting freshwater organisms, including fishes like *B. badis*, *B. brucei*, *S. multifasciata* and *D. dangila* in the near future. The temperature shifts in freshwaters might enable broader distribution of meso-thermal and eurythermal fishes in streams and rivers[38]. Therefore, cold-water fishes of high altitude would face habitat vulnerability[38]. Following environmental homogeneity, warm adapted fishes might dominate the watershed. Furthermore, having a trend of low substrate coarseness and shelter availability, the highly adapted fishes of genus *Glyptothorax*, *Garra* and *Psilorhynchus* might face perils[22]. In agreement with a previous study[34], the present findings project a similar scenario of decreased fish diversity, these findings also emphasize siltation for the jeopardy of fish diversity of EH in the coming days.

Conclusion

This small-scale river represents the characteristic upland torrential rivers of the UB basin of EH. Most of these antecedent reaches have geo-morphic similarity courses and skewed geomorphological and environmental frames. Since a typical regional climate profile also drives them, this study infers a similar trend of climate-change impact for such characteristic small-scale freshwater reaches. These rivers also act as thermal refuges for the inhabiting fish species, and their interaction with biotic and abiotic factors might face severe challenges due to climatic events in the coming days. Dispersal limitation, habitat specialization, anthropogenic pressure along with reduced heterogeneity of critical environmental factors in the near and distant future would lead to loss of piscine richness and diverse community structure in these small-scale reaches.

Ethical approval statement: The authors hereby declare fulfillment of all ethical commitments subjected to this research work.

Conflict of interest: The authors declare that there is no conflict of interest.

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