Ecological Indicators 108 (2020) 105735

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Water diversion induced changes in aquatic biodiversity in monsoon-dominated rivers of Western Himalayas in Nepal: Implications for environmental flows

Ram Devi Tachamo Shah[a,*], Subodh Sharma[a], Luna Bharati[b]

[a] Aquatic Ecology Centre, Kathmandu University, Dhulikhel, Nepal
[b] International Water Management Institute, Nepal

ARTICLE INFO

Keywords:
Himalayan headwaters
Rheophiles
Irrigation
Micro-hydropower
Water diversions

ABSTRACT

Water diversion projects across the world, for drinking water, energy production and irrigation, have threatened riverine ecosystems and organisms inhabiting those systems. However, the impacts of such projects on aquatic biodiversity in monsoon-dominated river ecosystems are little known, particularly in Nepal. This study examines the effects of flow reduction due to water diversion projects on the macroinvertebrate communities in the rivers of the Karnali and Mahakali basins in the Western Himalayas in Nepal. Macroinvertebrates were sampled during post-monsoon (November), baseflow (February) and pre-monsoon (May) seasons during 2016 and 2017. Non-metric Multidimensional Scaling (NMDS) was performed to visualize clustering of sites according to percentage of water abstractions (extraction of water for various uses) and Redundancy Analysis (RDA) was used to explore environmental variables that explained variation in macroinvertebrate community composition. A significant pattern of macroinvertebrates across the water abstraction categories was only revealed for the baseflow season. NMDS clustered sites into three clumps: "none to slight water abstraction (< 30% – Class 1)", "moderate water abstraction (> 30% to < 80% – Class 2)" and "heavy water abstraction (> 80% – Class 3)". The study also showed that water abstraction varied seasonally in the region (Wilk's Lambda = 0.697, $F_{(2,\ 28)} = 4.215$, $P = 0.025$, $n^2 = 0.23$). The RDA plot indicated that taxa such as *Acentrella* sp., *Paragenetina* sp., *Hydropsyche* sp., *Glossosomatinae*, Elmidae, Orthocladiinae and Dimesiinae were rheophilic i.e. positively correlated with water velocity. Taxa like *Torleya* sp., *Caenis* sp., *Cinygmina* sp., *Choroterpes* sp., Limonidae and Ceratopogoniidae were found in sites with high proportion of pool sections and relative high temperature induced by flow reduction among the sites. Indicator taxonomic groups for Class 1, 2 and 3 water abstraction levels, measured through high relative abundance values, were Trichoptera, Coleoptera, Odonata and Lepidoptera, respectively. Macroinvertebrate abundance was found to be the more sensitive metric than taxonomic richness in the abstracted sites. It is important to understand the relationship between flow alterations induced by water abstractions and changes in macroinvertebrates composition in order to determine sustainable and sound management strategies for river ecosystems.

1. Introduction

Freshwater ecosystems occupy < 0.1% of the Earth surface and yet provide habitats to about 10% of known biodiversity (Balian et al., 2008). In addition to being biodiversity hotspots, freshwater ecosystems also supply water for drinking, as well as for industrial uses and energy production. Today, humans have modified over three quarters of global large rivers and nearly no free flowing rivers exist in developed nations (Dynesius and Nilsson, 1994; Grill et al. 2019; Nilsson et al., 2005). River modifications alter flow regimes, causing a wide range of hydromorphological and ecological change (Caiola et al., 2014; Papadaki et al., 2016; Poff and Zimmerman, 2010; Schneider and Petrin, 2017). Alteration of stream flow characteristics due to water diversion projects may affect the health of river ecosystems and instream biotic communities, contributing to a loss of sensitive biota and enhancement of tolerant biota, sediment transport, and changes in nutrient availability and river beds (Bunn and Arthington, 2002; Poff et al., 1997; Tonkin and Death, 2013; Ward and Stanford, 1983).

In Nepal, water resource development is still underdeveloped. Though Nepal has nearly 42,000 MW of hydropower capacity, < 1000 MW has

* Corresponding author.
E-mail addresses: ramdevi.env@gmail.com (R.D. Tachamo Shah), subodh.sharma@ku.edu.np (S. Sharma), L.bharati@cgiar.org (L. Bharati).

https://doi.org/10.1016/j.ecolind.2019.105735
Received 19 October 2018; Received in revised form 9 September 2019; Accepted 12 September 2019
Available online 21 September 2019

Fig. 1. Locations of sampling sites in headwaters of Mahakali and Karnali River basins. From left- right: SNP = Suklaphata National Park; KNP = Khaptad National Park; RNP = Rara National Park; BNP = Bardia National Park; SPNP = Shey-phoksundo National Park; DHR = Dhorpatan Hunting Reserve.

been realized hitherto. Considering the potential of water resource development to aid in social and economic development, Nepal has aimed to generate about 25,000 MW of electricity by the end of 2030 (GoN/WECS, 2013) and many of these projects are planned in the Karnali and Mahakali river basins of Western Himalaya. It seems likely that many tributaries and sections of large rivers will be dammed in the next couple of decades, which will alter river flows in downstream sections of dams and reservoirs. Currently, the headwaters of Karnali and Mahakali basins are relatively unaffected by large-scale development. However, water diversion projects are prolific, mainly for irrigation, water mills and micro-hydropower (Fig. 1). Water is tapped from the source causing downstream river sections to have little or no water, despite the "Irrigation policy of Nepal (GoN/WECS, 2002)" mandating that the minimum water level required for the conservation of aquatic organisms living in the river ecosystems needs to be maintained. The ecological consequences of these water abstractions, however, are poorly assessed. In river ecosystems, benthic macroinvertebrates are considered one of the best bio-indicators for assessing the impacts of wider ranges of water pollution, climate change and flow alteration as they respond positively or negatively to these stressors (Dewson et al., 2007a; Poff and Zimmerman, 2010). Biotic indices based on benthic macroinvertebrates are common around the world (*sensu* DePauw and Hawkes, 1993). The most common ecosystem changes associated with an observed negative response of these indicator species include a decline in taxonomic richness, shift in relative abundance of certain organisms and reduction in biomass production (Holt et al., 2014). With hydrological changes, many of these aquatic insects have been found to be less abundant in low flows (Lenat, 1993) as river flows exert physical forces that influence water chemistry, nutrient cycle and habitat availability (Dewson et al., 2007b). As reliable bio-indicators, orders Ephemeroptera, Plecoptera and Trichoptera (EPT) are useful for ecological assessment of rivers to understand impacts of development of water resources (Holt et al., 2014). In this study, we assessed the ecological consequences of water diversion projects (especially irrigation projects, water mills and micro-hydropowers) on river health, by observing how indicator species respond to the changes in flow regimes. We anticipated that the increasing degree of water abstraction would result in reduced taxonomic richness and abundance of indicator taxa. We tested this hypothesis by looking at responses of macroinvertebrate assemblages in abstracted stream reaches and compared them to that at natural (reference) sites.

2. Materials and method

2.1. Study area

The Mahakali and Karnali River basins are the least disturbed river basins in Nepal. The headwaters are free from modern urbanization, and although there is organic pollution and regular influx of sewage into the rivers, the amount is minimal, thus offering a relatively controlled environment to assess the effects of water diversion projects on biotic communities.

The Mahakali River flows from the northern part of India and only 34% of the basin lies within Nepal. The Karnali basin has a catchment area of 127,950 sq. km of which 55% falls in Nepal (WSHP, 2007). About 14% of the total basin is under protection as national parks (7%), wildlife reserves and conservation areas. The Karnali River originates from the southern part of the Tibetan Plateau and is one of the main tributaries of the Ganges River system. At 507 km, the river is the longest in Nepal. The entire western Nepal is also a rain-shadow area as Western Nepal receives less than half the rain (1,000 mm annual rainfall) that Eastern Nepal does (2,500 mm annual rainfall) (GoN, 2008). Therefore, the region is considered as an arid zone that lacks riparian vegetation and canopy coverage in the rivers (Tachamo Shah's field survey 2016–2017). About 80% annual rainfall occurs in four months of the year from June –September.

2.2. Sampling sites

A total of 33, 41 and 40 (excluded one dried river reach) river reaches were sampled for post-monsoon (November), baseflow (February) and pre-monsoon (May) seasons, respectively, in the headwaters of Mahakali and Karnali River basins in 2016 and 2017 (Fig. 1). The sampling sites were distributed in rivers of High-Mountain, Mid-

Hills and Lowland eco-regions with road accessibility. All sites were mostly free from direct industrial or sewage influxes and waste dumping. Screening protocols (Hartmann et al., 2010) an effective tool to assess impacts of organic pollution) consists of 4 components: Sensory features (ordor, non natural color, foam and solid wastes); Ferro-sulfide reduction; Algae and periphyton coverage; and richness and abundance of benthic macroinvertebrates, were filled in at each site and only River Quality Class (RQC) I and II (High and Good river quality status, respectively) were selected for this study. Rivers with and without water diversions were considered as disturbed and natural (reference) sites, respectively. At disturbed sites, rivers were run-of-the-river systems with weir height < 2 m diverted for domestic, agricultural, water-mill operation and micro-hydropower generation.

Physico-chemical parameters such as pH, water temperature, conductivity, total dissolved solids (TDS) and dissolved oxygen saturation (%) were measured by a HANNA multi-parameter probe on site. Velocity was measured at 0.6 times of total water depth from water surface by using Global Flow Probe (Xylem brand) at 1 m interval across the wetted river channel. Discharge was calculated from velocity and cross-sectional area of wetted river channel. Proportion of flow types such as %riffle, %run and %pool within sampling stream reach was visually estimated before sampling benthic macroinvertebrates.

2.3. Benthic macroinvertebrates sampling and processing

At each selected site, about 50–100 m river reach was sampled for benthic macroinvertebrates. A total of 10 sub-samples from different substrates were collected at each site and combined to make one composite sample (Tachamo Shah et al., 2015). The substrate coverage was estimated at 10% intervals. Increase in specific substrate coverage increased number of sub-samples from that particular habitat. Benthic samples were collected by placing a hand-net of mesh size 500 µm against the flow of the river and disturbing the substrate for a minute to dislodge macroinvertebrates attached to surfaces of boulder, cobble, stone, gravel or sand (Barbour et al., 1999). The collected benthic macroinvertebrates were preserved in a sample bottle containing 80% ethanol for further laboratory analysis. Substrate type, depth and velocity at the site were recorded for each sub-sample prior to benthic sample collection. In the laboratory, benthic samples were sorted and identified at genus (mainly Ephemeroptera, Plecoptera, Trichoptera, Mollusca and Oligocheata except for Tubificidae), family (Coleoptera, Heteroptera, Odonata, Diptera, Lepidoptera and Megaloptera) and subfamily (Chironomidae and Psephenidae) levels using available keys (Morse et al., 1994; Assess-HKH internal keys, 2006; Nesemann et al., 2007; Nesemann et al., 2011). Identified samples were preserved in vials containing 80% ethanol at the Aquatic Ecology Centre of Kathmandu University.

2.4. Statistical analyses

The crossed anova was carried out to check for the effects of seasons and sites in taxonomic richness and abundance of benthic macroinvertebrates. Package “car” (Fox and Weisberg, 2019) was installed to perform the analysis.

Non-metric Multidimensional Scaling (NMDS) was used to group the sites according to seasons. Another NMDS plot was developed to examine the impact of water abstraction on composition of benthic macroinvertebrates. Sørenson’s distance measure was applied in the ordination plot in R software. NMDS ordination is a robust ordination technique for exploring similarities or dissimilarities in biological data as it does not require any assumptions of multivariate normality and yields good results even when large numbers of data sets have zero values (Clarke, 1993). Benthic macroinvertebrates abundance were transformed to log $(x + 1)$ prior to NMDS analysis. The first NMDS was performed on data representing three eco-regions – High Mountain, Mid-Hills and Lowland. The second NMDS was carried out excluding lowland and dam sites. Rare taxon with ≤ 3 individuals were removed prior to data transformation, reducing the taxa count from 174 to 139. Permutational Multivariate Analysis of Variance (PERMANOVA) was carried out with the Adonis function in R/vegan to test to check whether benthic macroinvertebrate assemblages differed significantly among seasons, eco-regions and water abstraction classes. The Bray-Curtis distance was used as distance measure in the community data.

A detrended correspondence analysis (DCA) was performed on benthic macroinvertebrate abundance to determine whether the distributions of the datasets are linear or unimodal (ter Braak and Smilauer, 2002). As the length of the first DCA axis (longest gradient) did not exceed 3.0 SD in benthic macroinvertebrate data (2.34 SD), the linear ordination method, redundancy analysis (RDA), was applied to explore how much variance in the benthic data could be explained by environmental variables, such as pH, conductivity, water temperature, oxygen saturation (%), total dissolved solids (TDS), water depth, water velocity, % riffle, % run and % pool. Prior to RDA, multicollinearity test was conducted and “TDS” was removed due to high collinearity ($r > 0.70$) in the final RDA plot. R “vegan” package was used in multivariate analysis.

Indicator species (Ind Val) analysis is widely used in long-term environmental monitoring for habitat or species conservation. Indicator species analysis seeks the relationship between species occurrence or abundance values from a set of sampled sites and classification of sites, which may represent habitat types or disturbance states. Indicator species analysis requires two components, namely, the community data matrix and the vectors that classify sites into groups (De Cáceres, 2013). It calculates relative frequency of species within group (Fidelity) and concentration of abundance within particular groups (Exclusivity). The Ind Val indicates the state of ecosystems by determining the effects of environmental change on biotic community within the study area. The Ind Val requires a package “labdsv” for running indval function in R software. All the analyses were performed in R package (R Core Team, 2018).

A one-way analysis of variance (ANOVA) was conducted to evaluate seasonal variation in the three water abstraction categories: none to slight abstraction (< 30%), moderate abstraction (> 30 – < 80%) and heavy abstraction (> 80%) in sampling sites.

3. Results

3.1. Seasonal changes in macroinvertebrate community composition

A total of 112, 146, 119 taxa representing 68, 79 and 76 families of macroinvertebrates were recorded for post-monsoon (November), baseflow (February) and pre-monsoon (May) seasons, respectively. Families belonging to orders/classes: Ephemeroptera, Plecoptera, Trichoptera, Coleoptera, Diptera, Heteroptera, Odonata, Lepidoptera, Megaloptera, Oligochaeta and Mollusca were recorded in all three seasons while families representing Decapoda, Hirudinea, Hydrachnidia and Turbellaria were additionally recorded only in baseflow and pre-monsoon seasons. Overall taxonomic richness and abundances were not different among seasons at natural sites, but some groups were significantly different among seasons for abstracted sites.

The study revealed that Trichoptera was the dominant order followed by Diptera (Fig. 2). A total of 5 functional feeding groups (FFGs) were recorded in the study sites (Fig. 3a,b). Collector-gatherers and shredders shared over 30% and < 5% of taxonomic richness, respectively while predators and scrapers shared similar percentage (> 20%) of taxonomic richness for the seasons (Fig. 3a). Collector-gatherers were the most dominant taxonomic group and accounting for nearly 60% of overall benthic macroinvertebrates abundance. Shredders made up < 2% of overall benthic macroinvertebrates abundance across the three seasons (Fig. 3b). Collector-filterers were found to be more stable

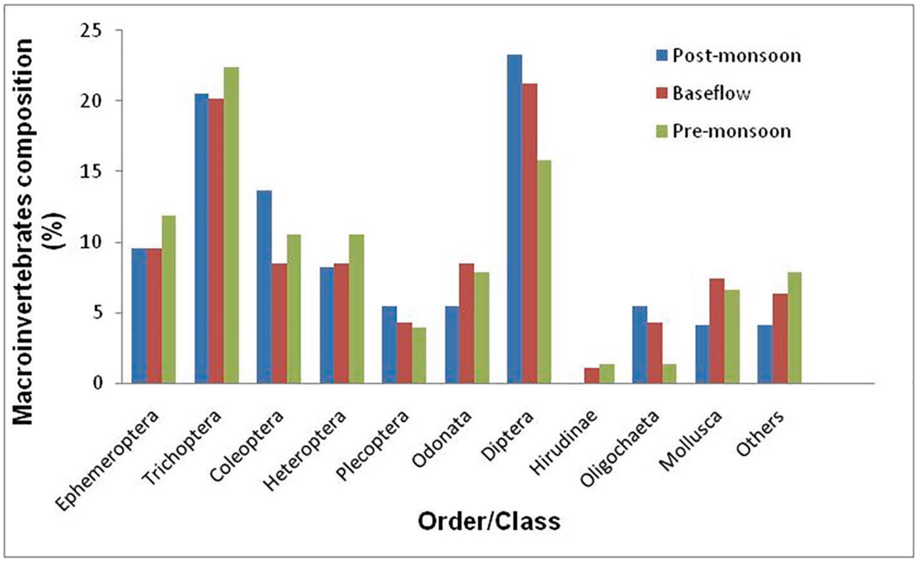

Fig. 2. Faunal composition of benthic macroinvertebrates across seasons. Others comprise of Lepidoptera, Megaloptera, Hydrachnidia and Decapoda.

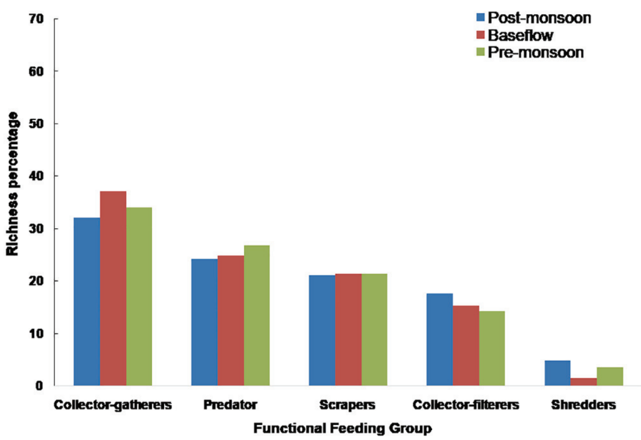

Fig. 3a. Functional Feeding Groups (FFGs) relative richness across seasons.

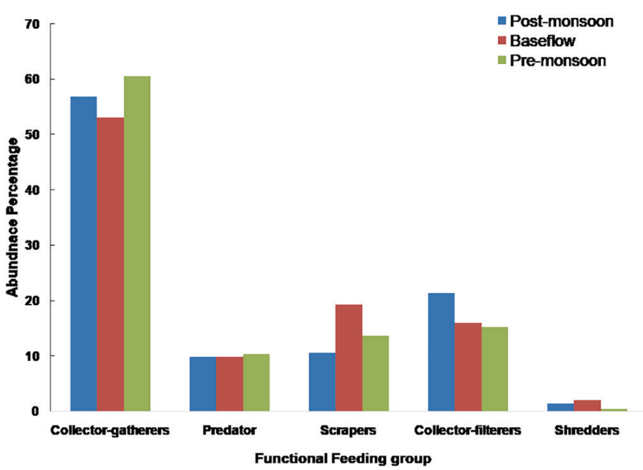

Fig. 3b. Functional Feeding Groups (FFGs) relative abundance across sampling seasons.

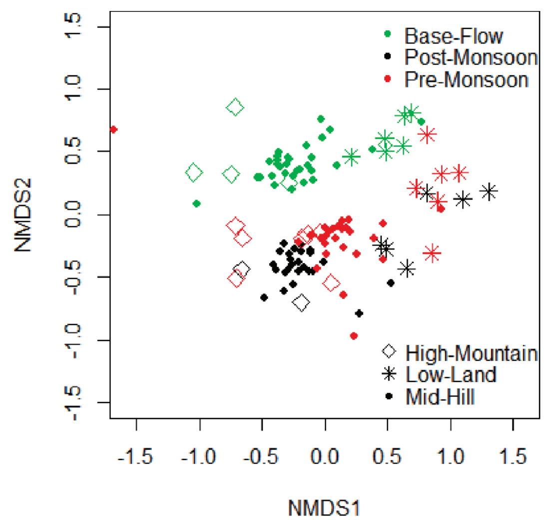

Fig. 4. Distribution of sites in NMDS ordination plot revealing groups of sites per seasons and eco-regions.

in terms of both richness and abundance (15–21%). No significant difference in composition and richness of FFGs between natural and abstracted sites were found for any of the seasons.

In the NMDS ordination for all sites, the distribution of sampling sites reflected both seasonality and eco-regions (stress = 0.175; Fig. 4). The sampling sites of the baseflow season (see Fig. 4) were located in the upper portion of the ordination map, while the sites of the post-monsoon and pre-monsoon seasons were located at the bottom of the ordination map. Despite abstraction intensity, sites were clustered by eco-region revealing similar community structure in sites of an eco-region. PERMANOVA revealed that there were significant differences in benthic macroinvertebrates assemblages across seasons ($F = 15.059$, $df = 2$, $p < 0.001$) and eco-regions ($F = 9.2149$, $df = 2$, $p < 0.001$). High mountain values are clumped to the left in the ordination map while Mid-Hill symbols and Lowland sites spread in the middle and to the right respectively in the ordination map, revealing spatial differences in benthic macroinvertebrate assemblages across the three eco-regions. Abstractions of river water were difficult to record in Lowland sites, and clustered with dam sites in Mid-Hill sites. Therefore, a second NMDS plot was created only for sites of High-Mountain and Mid-Hills to visualize clustering of sampling sites across different water abstraction categories (Fig. 5). PERMANOVA indicated differences among 3 water abstraction categories i.e., none to slight abstraction (< 30%), moderate abstraction (> 30 – < 80%) and heavy abstraction (> 80%) ($p = 0.047$).

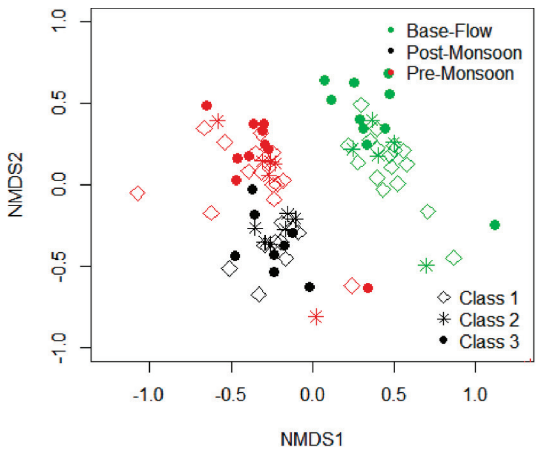

Fig. 5. Clustering of seasonal sites across 3 water abstraction classes. Significant clusters of sites as per water abstraction classes are presented in polygons for baseflow season (green points).

3.2. RDA analysis

The first two axes, roughly associated with velocity and water temperature, explain 66% of the taxonomic variance, with eigenvalue of $\lambda1 = 0.050$ and $\lambda2 = 0.028$, respectively. Three RDA axes were found highly significant (RDA1, F = 10.6279, df = 1, p = 0.001; RDA2, F = 6.7487, df = 1, p = 0.001, RDA3, F = 3.184, df = 1, p = 0.006). The sum of canonical eigenvalues was 0.2326. The RDA biplot (Fig. 6) illustrates the correlations of environmental variables and computed axes. The highest R^2 of regression with the first two axes were water velocity (32%) and temperature (18%), with velocity associated with the second axis and temperature mostly with the first. A strong negative correlation existed between the first axis and water temperature (r = -0.50), while oxygen saturation (DO%) correlated positively (r = 0.27). The second axis correlated strongly with velocity (r = −0.68), riffle (r = −0.43) and water depth (r = −0.34).

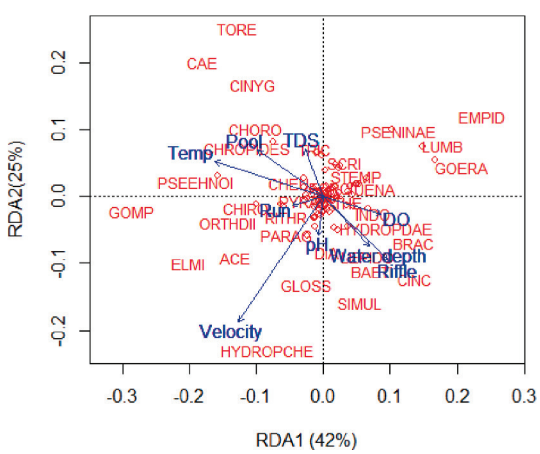

Fig. 6. RDA biplot of exploring environmental variables explaining variance in benthic macroinvertebrate communities. Taxa abbreviations are TORE = *Torleya* sp., CAE = *Caenis* sp., CINYG = *Cinygmina* sp., CHORO = *Choroterpes* sp., CHOROPIDES = *Choroterpides* sp., PSEEHNOI = Psephenoidinae, CHET = *Chematopsyche* sp., GOMP = Gomphidae, CHIRO = Chironominae, RITHRO = *Rithrogena* sp., ORTHDII = Orthocladiinae, ELMI = Elmidae, ACE = *Acentrella* sp., PARAG = *Paragnetina sp.*, GLOSS = Glossosomatinae, HYDROPSCHE = *Hydropsyche* sp., SIMUL = Simullidae, CINC = *Cincticostella* sp., BAETI = *Baetiella* sp., BRAC = *Brachycentrus* sp., INDO = *Indonemoura* sp., GOERA = *Goera* sp., LUMB = Lumbriciidae, EMPID = Empididae, PSENINAE = Psepheninae (anticlockwise). Significant environmental parameters are Temp = Temperature, Pool, Riffle and Velocity.

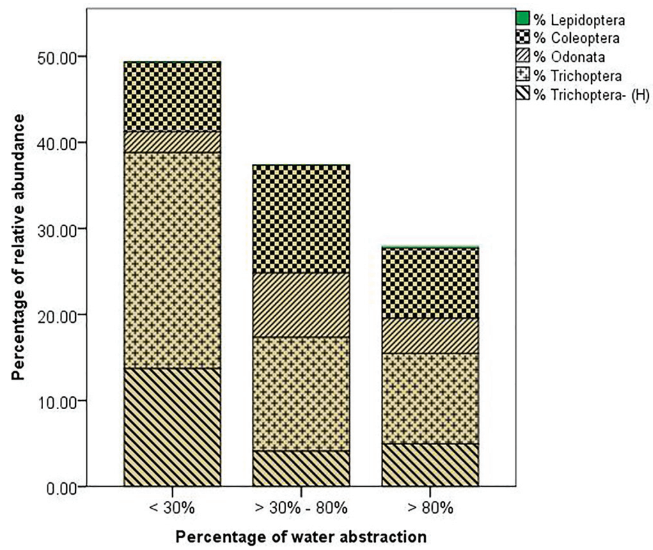

Fig. 7. Significant indicator taxonomic orders for water abstraction class.

3.3. Indicator species analysis

Indicator species analysis identified four indicators, namely, relative Trichoptera abundance for “None to Slight water abstraction”, relative Coleoptera and Odonata abundance for “Moderate water abstraction” and relative Lepidoptera abundance for “Heavy water abstraction” for all seasons (Fig. 7). For pre-monsoon season, relative Trichoptera and total abundance were identified as indicator groups for “None to Slight water abstraction” and Heavy water abstraction”, respectively from their high relative abundances.

3.4. Seasonal variation in water abstractions

The results of the ANOVA indicated significant seasonal variations in water abstractions (Wilk’s Lambda = 0.697, $F_{(2, 28)} = 4.215$, p = 0.025, $n^2 = 0.23$). Follow up comparison tests indicated that water abstractions were significantly different during baseflow ($p < 0.04$) and pre-monsoon season ($p < 0.02$) compared to post-monsoon season, while no significant difference was observed between baseflow and pre-monsoon seasons (p = 0.21).

4. Discussion

The present study suggests that temporal change in river discharge accompanied by consistent water abstraction is a strong driver of benthic macroinvertebrate assemblage structure, including trait composition. Significant variations in abundance of benthic macroinvertebrates in sites across the seasons (R-squared = 0.1192, $F_{(5,96)} = 3.734$, p-value = 0.003) indicate that reduced stream flow alters benthic macroinvertebrates composition. Reduction in flow regimes affects macroinvertebrate abundance and composition due to alterations in food availability, nutrient flow and dispersal mechanisms (Dewson et al., 2007b, Kennedy and Turner, 2011). However, richness was found less affected across seasons, between natural and abstracted classes, or even among abstraction classes which might be due to replacement of lotic taxa by lentic taxa between early seasons (*sensu* Bogan and Lytle, 2012). In this study, we found that some of the sensitive trichopteran in baseflow and pre-monsoon seasons were replaced by lentic taxa such as Depapoda, Hirudinea and Hydrachnidia. Our results highly supports the general findings that increase water diversions reduces river discharge in downstream river stretches affecting biological community (Anderson et al., 2015, Castella et al., 1995, Dewson et al., 2007b, McIntosh et al., 2002,). The altered

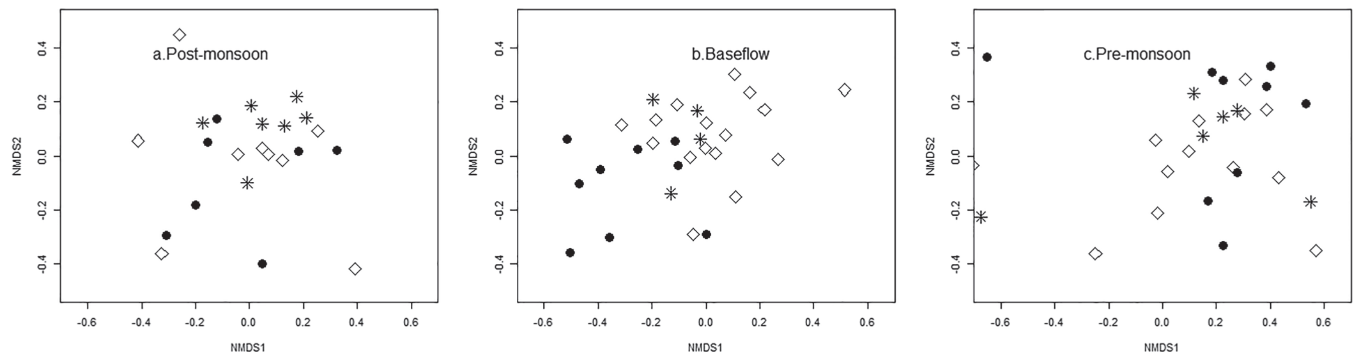

Fig. 8. NMDS plots for (a) post-monsoon, (b) baseflow and (c) pre-monsoon seasons. Symbols “Diamond” (◊), “Filled circle” (●) and strikes (✱) represent sites belonging to Class 1 (water abstraction < 30%), Class 2 (water abstraction > 30 – < 80%) and Class 3 (water abstraction > 80%).

macroinvertebrate community composition in the reduced flows in the regions is mainly dominated by sensitive taxa with tolerance scores above 4 which contradicts community composition in urban river reaches dominated by tolerant taxa of tolerance scores below 4 (Tachamo Shah and Shah, 2013). The river reaches in urban areas are stressed not only by water diversions but also influenced by organic pollutions and river bed mining. Water diversions that lead to river channelization can even cause serious impacts on diversity and density of aquatic organisms. A study conducted by Kennedy and Turner (2011) found 50% lower of benthic macroinvertebrates in channelized reaches.

Although it was difficult to disentangle macroinvertebrates variation across the three water abstraction categories in the NMDS plot (Fig. 5), distinct patterns of benthic macroinvertebrates across three water abstraction categories could be visualized in the season-specific NMDS plot for the baseflow season ($F = 2.087$, $R^2 = 0.126$, $p = 0.008$) (Fig. 8a–c). At sites of intensive water abstraction, a prolonged dry season can dry out downstream river segments making habitats unsuitable for colonization by organisms. Existing organisms may escape these habitats as well (e.g., Lytle et al., 2008) which was true in this study for heavily abstracted sites in particular Chipke River (Fig. 9a, b). Loss of longitudinal connectivity of river could influence long-term abundance of macroinvertebrates downstream due to failure of drifts of these organisms (*sensu* Brewin and Ormoerod, 1994b).

In general, EPT taxa are sensitive to flow alteration (Lenat, 1993) and abundance of EPT increases in high stream flows (Holt et al., 2014). Our results partly corroborate the findings of Holt et al. (2014) as abundance of Trichoptera (T) was lower at sites of increased water abstraction. Likewise, many of the EPT taxa were found positively associated with water velocity and riffles (Fig. 6). “Water Abstraction (Moderate) – Class 2” samples had increased abundance of Coleoptera and Odonata species indicating that river habitat alteration might have favored colonization of tolerant species (occurring in warm water and low flows) as opposed to more sensitive groups such as Trichoptera [occurring in adequate flows that provide clean, cool and oxygenated water (Brown et al., 1999, Timbol and Maciolek, 1978)]. Contrary to results from Castella et al. (1995) who assessed impacts of water abstractions for public water supply, energy production, fish farming and irrigations, our results did not demonstrate strong patterns of changes within many taxonomic groups. Sabater et al. (2018) have reported that that reduced flow regime due to irrigational water abstraction and channelization showed minor effects on river organisms, especially benthic macroinvertebrates, compared to when the flow was altered by dam operation but see Kennedy and Turner (2011). This is because dams completely (storage) or partially (fish ladders or release gates) block water flow, while irrigation water abstraction or channelization are run-of-river models allow where water continues to flow downstream of the intervention.

Since this study was conducted in rivers that were mainly affected by water diversions for irrigation, operations of micro-hydropower and water mills, changes in water quality parameters were not much distinguished in this study i.e., maintaining water quality parameters well above suitable to aquatic biodiversity. Reduced flows are known to affect physical and chemical characteristics of refugial waterbodies. In particular, the conductivity and diel temperature ranges usually increase, and dissolved oxygen concentrations usually decrease as waterbodies dry out (Boulton and Suter, 1986, Sheldon and Fellows, 2010). Increased water abstractions create unfavorable conditions for rheophilic macroinvertebrates (Castella et al., 1995, Fenoglio et al., 2007) such as the trichopterans. In abstracted sites, rheophiles are normally replaced by lentic or tolerant species (Death et al., 2009; Boix

Fig. 9. a) Chipke downstream during dry-period of sampling. Since, it was dried during pre-monsoon season, benthic samples did not collect for the season and collected only in post-monsoon and baseflow seasons and b) macroinvertebrates: Corydalidae belonging to Megaloptera found below the stone of recently dried river reach.

et al., 2010). Therefore, it is not surprising that abstracted sites in this study are favored by non-rheophilic groups such as Coleoptera, Odonata and Lepidoptera. We found many tolerant taxa such as *Caenis* sp., Chironominae, *Cheumatopsyche* sp., *Choroterpis* sp., Empididae, Lumbricidae etc. associated with high temperature, total dissolved solids and pool sites (Fig. 7). Elevated water temperature could enhance pupation frequency and emergence rate in macroinvertebrates (Verdonschot et al., 2015, Wooster et al., 2016). Similarly, Sabater et al. (2018) found a three-fold increase in downstream river metabolism as indicated by increased gross primary productivity and respiration as a response to accumulation of organic matter in low flow associated to damming and water abstraction.

In headwaters, availability and quality of food resources to benthic macroinvertebrates are depended on amount of allochthonous organic matters inputs from river banks (Vannote et al., 1980). Shredders and collector-gatherers make best foods out of the allochthonous inputs in the headwater reaches. But weak connection between river channel and riparian zone induced by low river discharges in the headwaters resulted decline numbers of shredders and collector-gatherers. These findings are corroborated with the results that hydrological modified sites have low diversity of collector-gatherers and shredders compared to natural sites (McKay and King, 2006; Dewson et al., 2007a). Changes in feeding groups might be due to reduction in trichopteran individuals in abstracted sites as they are sensitive to reduced flow regimes (McKay and King, 2006). On contrary, increased scrapers during low-flow seasons might be due to growth of algae which are enhanced with reduced flow and increased water temperature. Though our study illustrated small effects of water diversions on benthic macroinvertebrate community, the consequences of long term water diversion projects in river networks could have severe effects in water stress regions like in western Himalaya (*sensu* Boix et al., 2010; Boulton, 2003; Sabater et al., 2018).

In our study, some of the sampling sites, for example, Chipke River in the Karnali River basin and Ghatte River in the Mahakali River basin, were found dry during the pre-monsoon sampling season due to same quantity of water abstractions as in other seasons though there is naturally less flow in the season. Dewatering of stream reaches inhibits drifting of larvae downstream and upstream migration of juveniles of species (Brasher, 2003; Brewin and Ormerod, 1994a). The most important finding from this study was that macroinvertebrates richness did not significantly change even at > 80% of water abstraction. Similar results were recorded in an experimental flow-diversion study in New Zealand where a reduction in discharge by up to 90% caused relatively few effects on macroinvertebrate abundance and composition (James and Suren, 2009). With reduction in flow regimes, habitat and volume contract that in turn increases abundance and richness of macroinvertebrates and fishes in the short-term (Acuña et al., 2005; Stubbington et al., 2011).

Our study emphasized some of the effects of water diversion on headwaters of Western Himalaya, such as reduced abundance of rheophiles (Trichoptera taxa) and increased frequency and abundance of non-rheophilic taxa of Coleoptera, Odonata and Lepidoptera in disturbed sites. Our study provides evidence of abstraction effects on the phenology of sensitive species of macroinvertebrates which are the primary consumers, detritivores and prey in aquatic ecosystems.

In summary, the impact of water diversions in headwaters had little impact on benthic macroinvertebrates assemblages and river health in the Western Himalayas in Nepal. Water abstraction < 80% of the driest period (baseflow) of the year did not seem to influence benthic macroinvertebrates diversity and abundances in headwaters of the Himalaya under least hydro-morphological changes and pollution status in the rivers. It can be speculated that environmental flow atleast of 20% of river discharge for baseflow season should have minimum consequences on the benthic macroinvertebrate community composition in the headwaters of Western Himalaya. However, reduction in flow discharge in rivers coupled with increased water temperature and pollution due to waste discharge from the settlement into rivers and extraction of river beds is likely to impact benthic macroinvertebrate community and hence affect river health. This study demonstrates that run-of-river water diversions have little impact on river health and macroinvertebrate community composition in River Quality Classes (RQC) I and II (i.e., High and Good river quality status, respectively).

Acknowledgements

The project was made possible through funding from the United States Agency for International Development (USAID), U.S. Embassy, Kathmandu, Nepal. Grant Award Number: AID-367-IO-16-00002. Authors are thankful to Ms. Claire Swingle (IWMI – Princeton in Asia) for English editing of the manuscript. Authors are grateful to Dr. Kashmira Kakati and Netra Sharma (Sapkota USAID, Nepal) and anonymous reviewers for many helpful comments and constructive suggestions.

References

Acuña, V., Muñoz, I., Giorgi, A., Omella, M., Sabater, F., Sabater, S., 2005. Drought and postdrought recovery cycles in an intermittent Mediterranean stream: structural and functional aspects. J. North Am. Benthol. Soc. 24, 919–933.
Anderson, D., Moggridge, H., Shucksmith, J.D., Warren, P.H., 2015. Quantifying the Impact of water abstraction for low head 'run of the river' hydropower on localized river channel hydraulics and benthic macroinvertebrates. River Res. Appl. 33, 202–213.
Assess-HKH internal keys, 2006. Development of an assessment system to evaluate the ecological status of rivers in the Hindu Kush-Himalayan region. .
Balian, E.V., Segers, H., Lévèque, C., Martens, K., 2008. The Freshwater Animal Diversity Assessment-an overview of the results. Hydrobiologia 595, 627–637.
Barbour, M.T., Gerritsen, J., Snyder, B.D., Stribling, J.B., 1999. Rapid bioassessment protocols for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates and fish. US Environmental Protection Agency, Office of Water, Washington, DC.
Bogan, M.T., Lytle, D.A., 2012. Severe drought drives novel community trajectories in desert stream pools. Freshw. Biol. 56, 2070–2081.
Boix, D., García-Berthou, E., Gascon, S., Benejam, L., Tornés, E., Sala, J., Benito, J., Munné, A., Solá, C., Sabater, S., 2010. Response of community structure to sustained drought in Mediterranean rivers. J. Hydrol. 383, 135–146.
Boulton, A.J., 2003. Parallels and contrasts in the effects of drought on stream macroinvertebrate assemblages. Freshw. Biol. 48, 1173–1185.
Boulton, A.J., Suter, P.J., 1986. Ecology of temporary streams—an Australian Perspective. In: De Deckker P., Williams W.D. (eds) Limnology in Australia. Monographiae Biologicae, vol 61. Springer, Dordrecht.
Brasher, A.M.D., 2003. Impacts of human disturbances on biotic communities in Hawaiian streams. Bioscience 5311, 1052–1060.
Brewin, P.A., Ormerod, S.J., 1994. Macroinvertebrate drift in streams of the Nepalese Himalaya. Freshw. Biol. 32, 573–584.
Brewin, P.A., Ormerod, S.J., 1994. The drift of macroinvertebrates in streams of the Nepalese Himalaya. Freshw. Biol. 32, 573–584.
Brown, L.R., Brasher, A.M., Harvey, B.C., Matthews, M., 1999. Success and failure of nonindigenous aquatic species in stream systems: Case studies from California and Hawaii. In: Claudi, R., Leach, J.H. (Eds.), Nonindigenous Freshwater Organisms: Vectors, Biology, and Impacts. Lewis Publishers, Boca Raton (FL), pp. 415–430.
Bunn, S.E., Arthington, A.H., 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. J. Environ. Manage. 30, 492–507. https://doi.org/10.1007/s00267-002-2737-0.
Caiola, N., Ibanez, C., Verdu, J., Munne, A., 2014. Effects of flow regulation on the establishment of alien fish species: a community structure approach to biological validation of environmental flows. Ecol. Ind. 45, 598–604.
Castella, E., Bickerton, M., Armitage, P.D., Petts, G.E., 1995. The effects of water abstractions on invertebrate communities in U.K. streams. Hydrobiologia 308, 167–182.
Clarke, K.R., 1993. Non-parametric multivariate analyses of changes in community structure. Aust. J. Ecol. 18, 117–143.
De Cáceres, M., 2013. How to use the indicspecies package (ver. 1.7.1). http://137.122.187.16/cran/web/packages/indicspecies/vignettes/indicspeciesTutorial.pdf.
Death, R.G., Dewson, Z.S., James, A.B., 2009. Is structure or function a better measure of the effects of water abstraction on ecosystem integrity? Freshw. Biol. 54, 2037–2050.
DePauw, N., Hawkes, H.A., 1993. Biological monitoring of river water quality. In: Walley, W.J., Judd, S. (Eds.), River Water quality monitoring and control. Aston University, Birmingham, pp. 87–112.
Dewson, Z.S., James, A.B.W., Death, R.G., 2007a. Invertebrate responses to short-term water abstraction in small New Zealand streams. Freshw. Biol. 52, 357–369.
Dewson, Z.S., James, A.B.W., Death, R.G., 2007b. A review of the consequences of decreased flow for instream habitat and macroinvertebrates. Journal of the North American Benthological Society 26, 401–415.
Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation of the river systems in the northern third of the world. Sci. 266, 753–762.
Fenoglio, S., Bo, T., Cucco, M., Malacarne, G., 2007. Response of benthic invertebrate

assemblages to varying drought conditions in the Po river (NW Italy). Italian Journal of Zoology 74, 191–201.
Fox, F., Weisberg, S., 2019. An R Companion to Applied Regression, third ed. Sage, Thousand Oaks CA URL: https://socialsciences.mcmaster.ca/jfox/Books/Companion.
GoN (Government of Nepal), 2008. National Capacity Self-assessment for Global Environment Management, Government of Nepal/ Ministry of Environment. UNDP; and Global Environment Facility, Science and Technology.
Government of Nepal, Water and Energy Commission Secretariat (WECS), 2002. Available at: https://www.wecs.gov.np/uploaded/irrigation-policy-2060.pdf (Accessed on 14 September 2019).
Government of Nepal, Water and Energy Commission Secretariat (WECS), 2013. National Energy Strategy of Nepal. Available at: http://www.wecs.gov.np/uploaded/National-Energy-Strategy-of-Nepal-2013.pdf (accessed on 21 August 2018).
Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, B.E., Meng, J., Mulligan, M., Nilsson, C., Olden, J.D., Opperman, J.J., Petry, P., Reidy Liermann, C., Saenz, L., Salinas-Rodriguez, S., Schelle, P., Schmitt, R.J.P., Snider, J., Tan, F., Tockner, K., Valdujo, P.H., van Soesbergen, A., Zarfl, C., 2019. Mapping the world's free-690flowing rivers. Nature 569 (7755), 215–221.
Hartmann, A., Moog, O., Stubauer, I., 2010. HKH screening: a field bio-assessment to evaluate the ecological status of streams in the Hindu Kush-Himalayan region. Hydrobiologia 651, 25–37.
Holt, C.R., Pfitzer, D., Scalley, C., Caldwell, B.A., Batzer, D.P., 2014. Macroinvertebrate community responses to annual flow variation from river regulation: an 11-year study. River Res. Appl. 31 (7), 798–807. https://doi.org/10.1002/rra.2782.
James, A., Suren, A., 2009. The response of invertebrates to a gradient of flow reduction – An instream channel study in a New Zealand lowland river. Freshw. Biol. 54, 2225–2242. https://doi.org/10.1111/j.1365-2427.2009.02254.x.
Kennedy, T.A., Turner, T.F., 2011. River channelization reduces nutrient flow and macroinvertebrate diversity at the aquatic terrestrial transition zone. part35. Ecosphere 2. https://doi.org/10.1890/ES11-00047.1.
Lenat, D.R., 1993. A biotic index for the southeastern United States: derivation and list of tolerance values, with criteria for assigning water-quality ratings. J. North Am. Benthol. Soc. 12, 279–290.
Lenat, D.R., 1993. A biotic index for the southeastern United States – derivation and list of tolerance values, with criteria for assigning water quality ratings. J. North Am. Benthol. Soc. 12, 279–290.
Lytle, D.A., Bogan, M.T., Finn, D.S., 2008. Evolution of aquatic insect behaviours across a gradient of disturbance predictability. Pro. Biol. Sci. 275 (1633), 453–462. https://doi.org/10.1098/rspb.2007.1157.
McIntosh, D., Benbow, M.E., Burky, A.J., 2002. Effects of stream diversion on riffle macroinvertebrate communities in a Maui, Hawaii, Stream. River Res. Appl. 18, 569–581 10.1002/rra.694.
McKay, S.F., King, A.J., 2006. Potential ecological effects of water extraction in small, unregulated streams. River Res. Appl. 22, 1023–1037.
Morse, J.C., Yang, L., Tian, L., 1994. Aquatic Insects of China Useful for Monitoring Water Quality. Hohai University Press, Nanjing pp XII + 570 ISBN 7–5630–0240–5.
Nesemann, H., Sharma, S., Sharma, G., Khanal, S.N., Pradhan, B., Shah, D.N., Tachamo, R. D., 2007. Aquatic Invertebrates of the Ganga River System (Mollusca, Annelida, Crustacea [in part]) vol. 1. Kathmandu.
Nesemann, H., Shah, R.D.T., Shah, D.N., 2011. Key to the larval stages of common Odonata of Hindu Kush Himalaya, with short notes on habitats and ecology. J. Threat. Taxa 3, 2045–2060.
Nilsson, C., Liermann, R., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the World's Large River Systems. Sci. 308, 405–408. https://doi.org/10.1126/science.1107887.
Papadaki, C., Soulis, K., Munoz-Mas, R., Martinez-Capel, F., Zogaris, S., Ntoanidis, L., Dimitriou, E., 2016. Potential impacts of climate change on flow regime and fish habitat in mountain rivers of the south-western Balkans. Sci. Total Environ. 540, 418–428.
Poff, N.L., Zimmerman, J.K.H., 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshw. Biol. 55, 194–205.
Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime. Bioscience 47, 769–784.
R Core Team, 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna https://www.R-project.org.
Sabater, S., Bregoli, F., Acũna, V., Barceló, D., Elosegi, A., Ginebreda, A., Marće, R., Mũnoz, I., Sabater-Liesa, L., Ferreira, V., 2018. Effects of human-driven water stress on river ecosystems: a meta-analysis. Sci. Rep. 8, 1–11. https://doi.org/10.1038/s41598-018-29807-7.
Schneider, S.C., Petrin, Z., 2017. Effects of flow regime on benthic algae and macroinvertebrates-A comparison between regulated and unregulated rivers. Sci. Total Environ. 579, 1059–1072.
Sheldon, F., Fellows, C.S., 2010. Water quality in two Australian dryland rivers: spatial and temporal variability and the role of flow. Mar. Freshw. Res. 61, 864–874.
Stubbington, R., Wood, P.J., Reid, I., Gunn, J., 2011. Benthic and hyporheic invertebrate community responses to seasonal flow recession in a groundwater-dominated stream. Ecohydrol 4, 500–511. https://doi.org/10.1002/eco.168.
Tachamo Shah, R.D., Shah, D.N., 2013. Evaluation of benthic macroinvertebrate assemblage for disturbance zonation in urban rivers using multivariate analysis: Implications for river management. J. Earth Syst. Sci. 122, 1125–1139.
Tachamo Shah, R.D., Sharma, S., Haase, P., Jähnig, S.C., Pauls, S.U., 2015. The climate sensitive zone along an altitudinal gradient in central Himalayan rivers: a useful concept to monitor climate change impacts in mountain regions. Clim Change 132, 265–278.
Ter Braak, C.J.F., Smilauer, P., 2002. CANOCO reference manual and user's guide to Canoco for Windows: Software for Canonical Community Ordination (version 4.5); Microcomputer Power, Thaca, NY, US.
Timbol, A.S., Maciolek, J.A., 1978. Stream Channel Modification in Hawaii, Part A: Statewide Inventory of Streams; Habitat Factors and Associated Biota Columbia (MO) US Fish and Wildlife Service. National Stream Alteration Team FWS/OBS-78/16.
Tonkin, J.D., Death, R.G., 2013. Macroinvertebrate drift-benthos trends in a regulated river. Fund. Appl. Limnol. 182, 231–245.
Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Gushing, E., 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37, 130–137.
Verdonschot, R., Oosten-Siedlecka, A.M., Braak, C.J., Verdonschot, P.F., 2015. Macroinvertebrate survival during cessation of flow and streambed drying in a lowland stream. Freshw. Biol. 60, 282–296.
Ward, J. V., Stanford, J. A., 1983. The serial discontinuity concept of lotic ecosystems. In: Fontaine, T.D., Bartell, S. M. (eds), Dynamics of Lotic Ecosystems. Ann. Arbor. Science: 29-42.
Wooster, D., Miller, S.W., DeBano, S.J., 2016. Impact of season-long water abstraction on invertebrate drift composition and concentration. Hydrobiologia 772, 15–30.
WSHP (West Seti Hydropower Project), 2007. Environmental Assessment Report of Nepal: West Seti Hydropower Project. Available at http://www.aecen.org/eia-documents/eia-west-seti-hydroelectric-project/nepal_eia_report_westsetihydroelectric_2007.pdf. Accessed on 15 June 2018.