



e-ISSN: 2319-8753 | p-ISSN: 2347-6710

IJRSET

International Journal of Innovative Research in
SCIENCE | ENGINEERING | TECHNOLOGY



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 13, Issue 9, September 2024

ISSN INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 8.524

9940 572 462

6381 907 438

ijrset@gmail.com

www.ijrset.com

Hydropower and Aquatic Ecosystems: A Study of Macroinvertebrate Diversity and River Health in Southern Bhutan

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ABSTRACT: A freshwater system is crucial for the survival of both biodiversity and human life, as it supports the world's highest biodiversity. Bhutan is richly endowed with abundant freshwater sources, including rivers, streams, springs, lakes, and ponds. To capitalize on the potential of its fast-flowing rivers in Bhutan, it has extensively developed hydropower plants in most major rivers. However, this development has come at the cost of environmental conservation, significantly impacting aquatic flora and fauna. This study assessed the community structure of macroinvertebrate diversity above and below the reservoir to observe the impact of hydropower construction. Additionally, the physiochemical parameters and biotic scores were also evaluated to determine the river's health condition above and below the dam. Samples were collected for two seasons, post-monsoon and winter. Multi-habitat sampling was carried out at an interval of 100 meter reach. A total of 1,628 individuals of 36 families under 10 orders were recorded of which 31 families inhabit sites above the dam and 27 families below the dam. Over all, Trichoptera was the most abundant (24%) whereas Annelida, Crustata and Megaloptera made up just 6%. The Shannon diversity unveiled no significant difference ($p > .05$) above and below the dam, however, diversity was higher above the dam ($H' = 2.71$) than below the dam ($H' = 2.45$). There was also no significant difference between the two seasons. However, the physiochemical characteristics of water above and below the dam were significantly different with water quality ranging from good to moderate. The study recommends including macroinvertebrate studies in the environmental impact assessment to monitor the long-term impact of hydropower projects.

KEYWORDS: Environmental impact assessment, macroinvertebrate, multi-habitat, physiochemical parameters, Shannon diversity, and water quality.

I. INTRODUCTION

Humans, animals, plants and microorganisms depend on freshwater ecosystems for survival. Freshwater accounts for 0.01% of Earth's water and just 1% of the planet's surface but it is home to the world's highest biodiversity (Dudgeon et al., 2006; Strayer & Dudgeon, 2010). Himalaya has huge stocks of water in the form of snow and ice, but it is fast receding faster due to climate change (Palmer et al., 2008; Singh et al., 2011; Sharma & Choudhury, 2021). Anthropogenic activities have caused severe degradation of fresh water, however very little attention has been received for conservation purposes around the world which requires a regular ecosystem integrity assessment (Lennox et al., 2018). Humans have constructed a variety of physical barriers, including dams, diversions, channels and embankments for various purpose (Brown, 2006; Angelakis et al., 2024). Bhutan, India, Pakistan and Nepal are undertaking massive hydropower development plans for the next twenty years. If the plans are materialized, the Himalayan region will have the highest concentration of dams in the world (Palmer et al., 2008). Dam constructions are traditionally perceived to be environmentally friendly but there are concerns associated with the planning; design, construction and operation of dams (Tortajada, 2015). Retaining and altering its natural flow from the reservoirs has led to changes in aquatic and terrestrial habitat structures above and below dams (Combes & Edds, 2005; Chakraborty & Chakraborty, 2021). It has also caused severe hindrance to aquatic ecological processes and the physical landform of the river system undermining the quality of water (Karna et al., 2015). The fluctuation of river volume has a consequent effect on habitat conditions, community structure, behaviour, species diversity and alteration of food resources influencing the organism behaviour and biotic interactions (Tockner et al., 2010); (Petry & Mahan, 2012). Macroinvertebrates are integral to river systems and play a crucial role in maintaining aquatic ecosystems. They are a controlling group in food webs, serving as a source of food for fish, amphibians, and water birds (Choudhury & Gupta, 2015). They are also involved in the

breakdown of organic matter and nutrients. Thereby playing an important role in biological, ecological and functional processes (Lin et al., 2020). The varying sensitivity to pollution makes it an important bio-indicator of stream health and is more appropriate for water stream quality assessment than chemical test (Shafie et al., 2017; Manzoor et al., 2021). The enduring preservation of freshwater ecosystems and their inhabitants significantly relies on protecting and recognising the fundamental biological, ecological, and physical processes in the system (Kwak & Freeman, 2010).

II. METHODOLOGY

Study Area: The 126 MW Dagachhu hydropower plant (27°25'02.9" N and 089°33'29.8" E) is located at an altitude of 985 masl in southern, Bhutan (Figure 1, A-Major Rivers under Dagana Dzongkhag, B.-Dagachhu watershed and other tributaries, C-Dagachhu river and sampling stations).

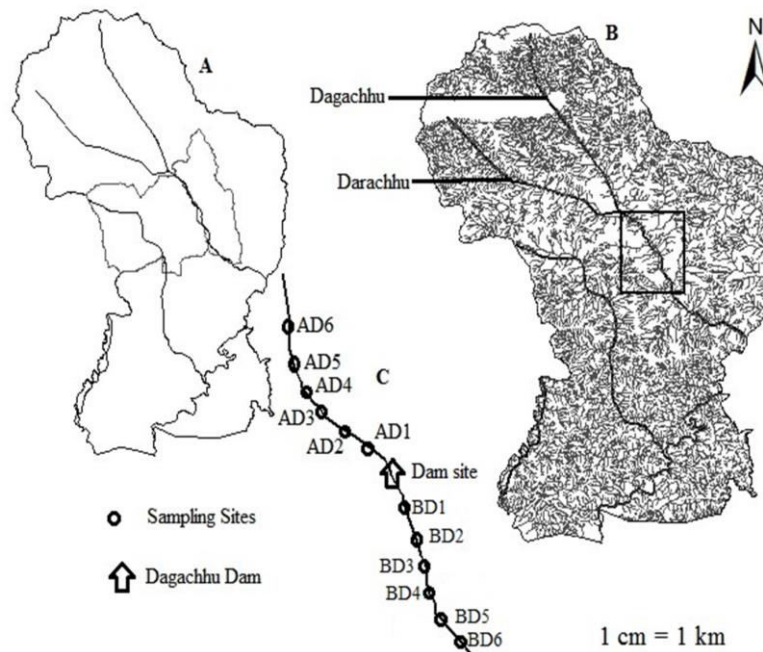


Figure 1

Sampling method: Benthic macro-invertebrates were sampled in early autumn and winter. The samples were being taken from above (AD1, AD2, AD3, AD4, AD5, and AD6) and below (BD1, BD2, BD3, BD4, BD5, and BD6) the dams. A total of 12 sampling stations were identified and samples were collected from six replicas each. A multi-habitat sampling collection was adopted based on (Barbour et al., 2006). The primary advantage of the multi-habitat approach is its ability to sample representative and multiple stream habitats, potential for quick and relatively inexpensive. The multi-habitat included; a pool, run, riffle and cascade along the stretch. A total of 1200 meters stretch was covered above and below the dam maintaining 100 meter intervals between stations. The D-Frame sampling method was adopted with a mesh net of 0.5 m x 0.5 m and a 500 µm size was used for sampling.

Macroinvertebrate sampling procedure

The distribution of the samples within the reach was systematic and four habitat types were selected within the 100 meters reach (Flotemersch et al., 2006). Kick and sweep techniques were used to collect the insects. It was also collected by dislodging the substratum by hand between boulder pockets, the bottom substrates were stirred by hand and released organisms into the D-frame net. Those macroinvertebrates identified in the field were released and others were taken to the laboratory for identification euthanized in 10% formalin and preserved in ethanol (Wangchuk and Eby, 2013). Identification up to the family level was carried out as per the recommendation (Melo & Froehlich, 2001). According to Tomanova et al. (2006) and (Gayraud et al., 2003) identification up to the family level for bio-monitoring purposes does not compromise the results. The chemical parameters such as temperature, pH, conductivity, total

dissolved solids and salinity were measured using PCSTestr 35 Multi-Parameter. The geographical coordinates were also recorded using the Global Positioning System (GPS).

Water quality assessment using HKHbios score

A benthic invertebrate-based scoring system, the Hindu Kush-Himalayan biotic score (HKHbios) was used to determine the quality of water (Ofenböck et al., 2010).

$$\text{HKHbios} = \frac{\sum_{i=1}^n \text{HKHbios-Score}_i * \text{Weight}_i}{\sum_{i=1}^n \text{Weight}_i}$$

Where HKHbios-Score_i is the HKHbios-score of taxon *i* and Weight_i is the weight of taxon *i*.

Data Analysis

The data compilation was done in MS Excel and analysed using SPSS software. Macroinvertebrate diversity was calculated using the Shannon Diversity Index ($H' = -\sum p_i (\ln p_i)$ where S = species richness, p_i = proportion of individuals belonging to i^{th} species or the relative abundance, \ln = natural logarithm). Population evenness above and below the dam was calculated using the Shannon Evenness formula ($E_H = H/H_{\text{max}} = H/\ln S$). Mann Whitney U test was run to test the significance of diversity above and below the dam. The differences in environmental variables above and below the dam were examined using the Kruskal Wallis test.

III. EXPERIMENTAL RESULTS

Macroinvertebrate diversity

The calculation of abundance, richness, diversity index (H') and Shannon evenness (E_H) was carried out at the family level. A total, 1,628 macroinvertebrates belonging to 36 families under 10 orders were recorded. The highest diversity was recorded above the dam in winter ($H' = 2.72$) followed by above the dam in post-monsoon ($H' = 2.44$), below the dam for post-monsoon ($H' = 2.20$) and lowest below the dam in winter ($H' = 2.19$). When the diversity index for two seasons was combined to assess the annual difference; above the dam ($H' = 2.71$) was higher compared to below the dam ($H' = 2.45$). The diversity index of macroinvertebrates conformed with what Flores & Zafaralla, (2012) have been observed to be between one and six. The higher diversity above the dam could be due to the continuous flow of water, lesser change in flow regime and pollution, lower disturbance and habitat disturbance. Conversely, lower diversity below the dam was attributed to pollution from construction materials dumping, polluted water discharge, water stagnation, decreased pH value, and reduced flow. Regular human disturbance through fishing and substantial metallic and plastic waste were left after the dam construction.

The diversity index was higher above the dam in winter than post-monsoon. The smooth flow of the river aids in the accumulation of decayed leaves, thereby creating favourable conditions for macroinvertebrates in winter. In contrast, lower diversity in the post-monsoon was mainly due to a rise in river volume scouring the river bed, and increased runoff entering the river leading to developed turbidity and heavy erosion of the river bed and bank. Similar observations like river bank eroding, sedimentation and habitat disturbance of aquatic organisms were reported by (Bowles & Arsuffi, 1993; Okeke et al., 2020).

The result shows 31 families above the dam and 27 families below the dam. The family distribution was more even above the dam ($E_H = 0.79$) than below the dam ($E_H = 0.74$). Similarly, species richness was higher above the dam ($SR = 4.47$) than below the dam ($SR = 3.76$) (Figure 2). The even distribution above the dam could be due to minimal human disturbances, better riparian forest conditions and an undisturbed flow regime. As reported by Flores and Zafaralla (2012), upstream stations will have higher diversity and richness than lower-lying stations of the same river.

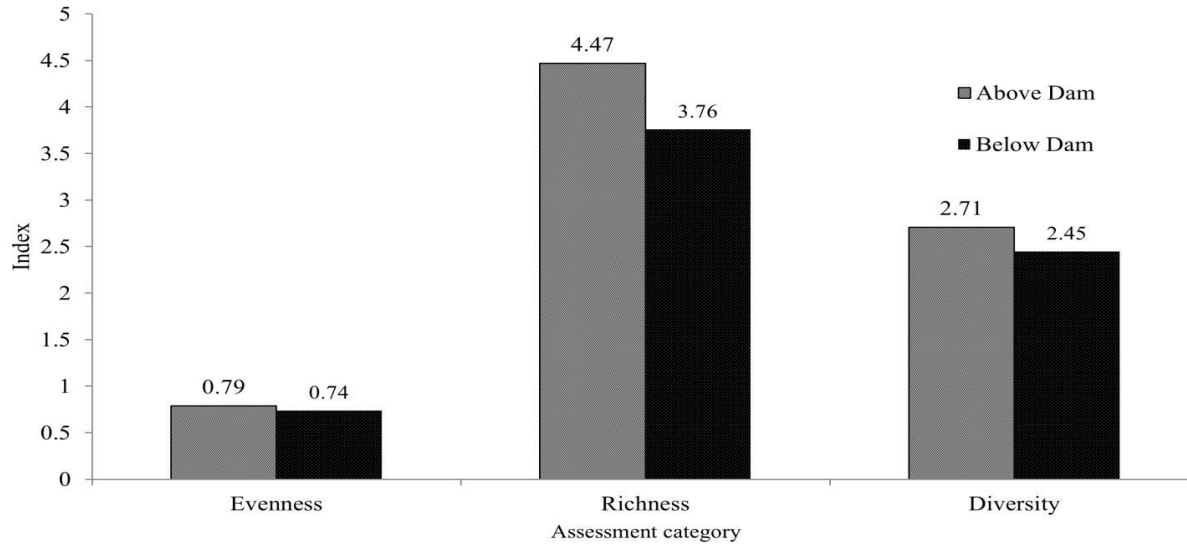


Figure 2. Macroinvertebrate condition

Macroinvertebrate assemblage

In the whole study area, the most diverse groups of macroinvertebrates were, Trichoptera (n = 11), Ephemeroptera (n = 10), Diptera (n = 8), followed by Plecoptera and Odonata (n = 4) each, whereas, Annelida, Crustata and Megaloptera were relatively low with just one family each (Figure 3). Trichoptera can adapt to varying habitat types and are found in most of the world and are most widely used for water quality assessment along with mayflies and stoneflies (Pirvu & Pacioglu, 2012). The differences in population structure could be because of the generalist nature of habitat requirement of individual species of macroinvertebrates (Al-Shami et al., 2011).

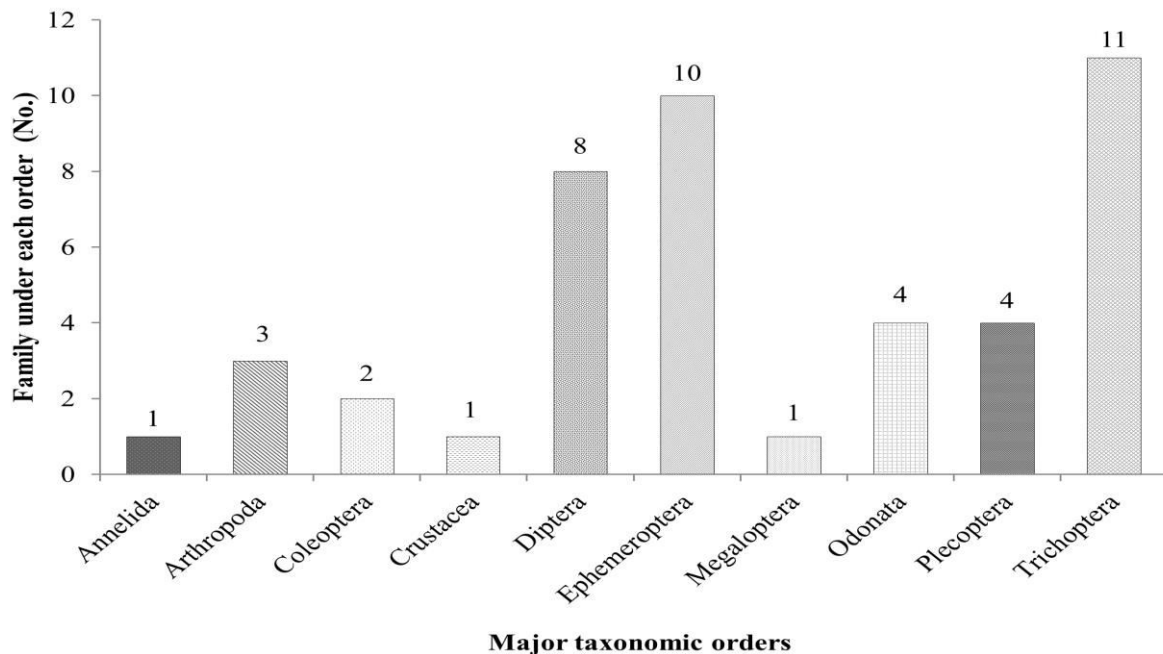


Figure 3. Families under each order combined for both above and below the dam

It was observed that Ephemeridae, Hydrochidae, Hydrophilidae, Lepidostomatidae, Lympridae, Neophemeridae, Psychomyiidae and Simuliidae were absent below the dam. Similarly, taxa that were absent above the dam were, Athericidae, Helicopsychidae, Isonychiidae, Leptophlebiidae and Psychodidae. Taxa with minimum count were, Brachycentridae, Ephemeridae Euphaeidae, Helicopsychidae, Hydrochidae, Isonychiidae Hydrophilidae, Leptophlebiidae, Lepidostomatidae, Lympridae, Neophemeridae, Psychodidae Psychomyiidae and Simuliidae. These rare taxa combined to form just 8.9% of the total assessed population. The most abundant taxa were Baetidae, Glossosomatidae, Heptageniidae, Hydropsychidae, Nemouridae, Perlidae, and Philopotamidae combined to form 63.87% of the total assessed population.

Among the abundant taxa, Glossomatidae, Heptageniidae, Hydropsychidae and Baetidae were extensive and rich in all habitat types. Furthermore, these taxa were not affected much by changes in the volume and velocity flow. Other factors like warmer water and adaptability to decreased pH must have created a suitable environment for its population to thrive. A similar study carried out by Nijboer (2004) reports that the habitat requirement for *Agapetus fuscipes curtis* (Glossosomatidae) is not affected by discharge dynamics and the species cope well by maintaining very high population density and can colonise the disturbed habitat.

Above the dam, Brachycentridae, Ephemeridae, Euphaeidae, Hydrochidae, Hydrophilidae, Lepidostomatidae, Lympridae, Perlodidae, Polycentropodidae, Potamidae, Psychomyiidae, Rhyacophilidae, Simuliidae, Stenopsychidae, Tabanidae, Tubificidae combined to form 12% of the assessed population. Brachycentridae, Ephemeridae, Gomphidae, Isonychiidae, Leptophlebiidae, Limoniidae, Polycentropodidae, Potamidae, Psychomyiidae, Tabanidae and Tubificidae were relatively low (3.36%) below the dam. A similar observation was reported by Sharma et al., (2005) in their case study in Tianu River in Nepal. However, sedimentation was found maximum above the dam which altered the habitat for some species.

Comparative differences of macroinvertebrates above and below the dam

Mann-Whitney U test was executed to test the significance of the diversity above and below the dam in summer and winter and also the annual differences above and below the dam.

There was no significant difference in diversity above and below the dam for both seasons. The post monsoon ($U = 109$, $p = .277$) and for winter season ($U = 223$, $p = .366$). Even annual diversity showed no significant significance between above and below the dam ($U = 394$, $p = .702$). However, diversity was comparatively higher for sites above the dam for both seasons. It was observed that during and post-monsoon the macroinvertebrate population was relatively low, which could have been contributed by stressors like heavy rainfall, riverbed eroding and increased volume and velocity. During the winter, the water is cut off by the dam and the water volume below the dam gets extremely low affecting many microhabitats. A similar finding was also observed by Xiaocheng et al. (2008) that significant habitat impacts were caused by regulating the flow of water in hydropower dams.

River health based on biotic index

The HKHbios score was used to determine the quality of the water since the study site was within the subtropical broad-leaf forest. The Eastern Himalayan Broadleaf Forest baseline was used to grade the quality of water. Although comprehensive details were provided in the guidelines it lacks biotic scores and weight for some of the families which hindered the accuracy of the result. However, there were not many differences in the biotic index between the sites with all sites securing moderate to good status (Table 1). Water quality below the dam in winter was found to be better than the rest of the sites with a biotic score of 7.93. It could have been influenced by a pristine stream joining right below the dam.

Table 1. Biotic score for study site

Location	HKH Biotic Index	EHBF	Condition
Above Dam Post Monsoon	7.42	≤ 6.3	Good
Below Dam Post Monsoon	7.61	≤ 6.3	Good
Above Dam Winter	7.49	≤ 6.3	Good
Below Dam Winter	7.93	≥ 7.7	Reference/Good

Physical parameter differences among the sites

The physiochemical parameters were also taken to assess the quality of water. The potential of Hydrogen (pH), Electrical Conductivity (EC), Total dissolved solids (TDS) and Salt content of the water was assessed (Table 3). These variables were tested for significant differences among sites and seasons. There was a significant difference in the physiochemical composition of water above and below the dam (Table 2).

Table 2. Kruskal Wallis significance test among sites

	Water Temperature	pH	EC	TDS	Salt
Chi-Square	21.675	17.535	21.619	19.792	19.792
df	3	3	3	3	3
Asymp. Sig.	.000	.001	.000	.000	.000

Two important observations were made from the analysis. There was an increase in water temperature and a decrease in pH value below the dam compared to sites above the dam (Table 3). In both seasons, there was a difference in mean water temperature. It was higher below the dam by 2.78°C in post-monsoon and 2.75°C in winter. The increased temperature below the dam in both seasons could be due to a sharp fall in water volume and prolonged sunlight penetration in the absence of good vegetation and crown cover. Lessard & Hayes (2003) report an observed increase in mean temperature below the dam between 1°C to 5 °C leading to a change in macroinvertebrate composition below the dam. The pH value of the water was found to be within the permissible range (6.5-8.5) of drinking water standards (World Health Organisation, 2024), in most of the sites except a station right below the dam was below normal with a pH of 6.31. The water quality has slightly deteriorated below the dam. It could be due to effluent from the dam site, reduced velocity, stagnation, reduced depth and contamination.

Table 3. Test result of seasonal variation physiochemical parameters

Season	Post Monsoon			Winter Season		
	Minimum	Mean	Max	Minimum	Mean	Max
Variables						
Water Temperature	19.10	20.25	21.88	11.35	12.64	14.10
pH	6.23	6.41	6.54	6.31	6.61	6.87
EC	25.40	30.64	38.13	51.25	55.29	59.88
TDS	20.82	23.63	27.65	37.33	39.67	42.33
Salt	22.63	25.82	30.37	26.30	28.36	30.70

IV. CONCLUSION

The macroinvertebrate diversity was relatively higher above the dam for both seasons; however, there were no significant differences. The occurrence of higher diversity above the dam was due to the absence of anthropogenic disturbances and relatively undisturbed habitats above the dam. In contrast, lower diversity below the dam was due to a substantial reduction of water flow from the dam whereby rendering the river beds almost dry in most of the year.

The overall health of the river was found to be in moderate to good condition based on the biotic index obtained using the HKHbios score. Due to a lack of scores for some of the prevalent taxa, results obtained may not be accurate and can be improved. Therefore, a national biotic scoring system for Bhutan is felt necessary to enhance the accuracy in evaluating aquatic health using bioindicators. A significant difference in the physiochemical content of the water above and below the dam was observed. There was an apparent increase in water temperature and decreased pH below the dam rendering a change in the habitat, population and community structure of macroinvertebrates below the dam. This condition was induced by the substantial decrease in the minimum environmental flow from the reservoir dam. Therefore, requirements of minimum environmental flow need to be strictly monitored to reduce water acidification due to stagnation and reduced water flow. The quantity, quality, and timing of environmental flow for dams, which often primarily consider fish requirements, should equally emphasize the needs of macroinvertebrates. These organisms are an integral part of the aquatic ecosystem and are essential for sustaining freshwater systems. The benthic macroinvertebrate being the basis of the food chain and an important indicator of stream health needs an equal

emphasis for habitat conservation. Hydropower companies have overlooked macroinvertebrates in environmental impact assessments, missing crucial long-term impact studies. Thus, detailed assessments of aquatic fauna, including fish, macroinvertebrates, and meiofauna, are essential during EIAs for all hydropower projects in Bhutan.

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