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Ecological Implications of Dam and Barrage Construction in the Indian Himalayan Region: A Comprehensive Assessment

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Abstract

Dams and barrages are vital infrastructure for human needs such as hydroelectric power generation, irrigation, and water storage, but their construction has significant negative impacts on the biodiversity and riverine ecosystem of aquatic species. The Indian Himalayan Region (IHR) is known for its unique ecological and environmental significance. However, the construction of dams and barrages in this region has raised concerns regarding their ecological consequences. This paper aims to assess the ecological impacts of dam and barrage construction in the IHR. The construction of dams and barrages in the IHR has resulted in significant alterations to the natural flow patterns of rivers, leading to changes in hydrology, sediment transport, and water availability. These alterations have had profound effects on the aquatic ecosystems, affecting fish populations, riverine habitats, and biodiversity. Furthermore, the fragmentation of rivers caused by dam construction has disrupted migratory patterns of several species, thereby impacting their breeding and survival. This paper provides an overview of the ecological consequences of dam and barrage construction in the Indian Himalayan Region, highlighting the need for sustainable and environmentally sensitive approaches to infrastructure development in this ecologically fragile region. By considering the ecological implications and adopting appropriate mitigation measures, it is possible to strike a balance between meeting the energy and water demands of the region while safeguarding its unique and diverse ecosystems.

Keywords: Dam and Barrages; Water Quality; River Hydrology; Feeding and Breeding Habit; Habitat Fragmentation; Aquatic Biodiversity

Abbreviations: IHR: Indian Himalayan Region; ROR: Run of the River; DO: Dissolved Oxygen; TDS: Total Dissolved Solids; EIAs: Environmental Impact Assessments.

Introduction

Dams are constructed on rivers to serve various purposes such as water storage, electricity generation, irrigation, and drinking purposes. Barrages are a type of dam constructed mainly for diverting water. Developing countries have approximately two-thirds of the world's large dams [1]. Dams can be categorized into different types based on their application, such as storage dams, diversion dams, detention dams, debris dams, and coffer dams.

Storage dams are multipurpose dams that function as water storage in the dry season and distribute water according to need. Diversion dams plays role in only irrigation and run-of-the-river (ROR) dams function as only hydropower generation, also single-purpose with providing low capacity and only minor effect on river regime [2]. Debris dams are constructed to reserve the debris material, such as sand and gravel, and for protection from floods, detention dams are constructed.

Large dams play a crucial role in the economic and social development of countries by providing services such as electricity generation [3,4]. The Indian Himalayan Region (IHR) covers a total area of more than 5.3 million km2 and spans a distance of over 2500 km between the Indus and Brahmaputra River systems. The IHR has three significant geographic regions: the Himadri (Greater Himalaya), Himanchal (Lesser Himalaya), and the Siwaliks (Outer Himalayas). Ten hill states such as Ten hill states – Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Nagaland, Manipur Mizoram, Tripura and Meghalaya–as well as two partially hill states, Assam and West Bengal, make up the Himalayan region. This region provides fresh water through rivers, lakes, and ponds.

However, the construction of dams causes a serious change in the quality of water by altering parameters such as air, temperature, TDS (Total Dissolved Solids), and DO (Dissolved Oxygen) [5-7]. The degradation of the environment and displacement of society is an essential issue regarding the decadence in the quality of water sources [1,8]. Dams change the flow of water, affecting the magnitude, timing, and duration of high and low flows [9]. Flow regulation is connected to hydrological changes, which impact the composition, structure, or function of the aquatic ecosystem by changing habitat characteristics such as water temperature, oxygen content, and water chemistry [10-12].

The construction of dams causes the habitat fragmentation, leading to the loss of alleles that affect the genetic structure [13-16]. Changes of water flow affect the spawning, digging, migrant behaviour of fish and also a negative effect on fish assemblage structure [5]. The construction of dam's affects aquatic life cycles, including microorganisms, plankton, benthos, and fish [17]. The abundance and production of phytoplankton increase in the area of the river where the dam is constructed [18]. Dams change the flow temperature, water quality, and substrate, ultimately affecting the diversity of benthos, such as macroinvertebrates and periphyton [19]. They also affect fish diversity through habitat fragmentation, changing water flow, and act as a barrier to fish migration [20].

Dams in Uttarakhand

Dams in Uttarakhand: Uttarakhand, a state in northern India, is known as Urja Pradesh or the energy state due to its significant contribution in generating more than 21,200 MW electricity through small and big hydroelectric projects. The Garhwal region in Uttarakhand is home to approximately 10 major rivers that support some 60–70 species of fishes within a short radius of 200 miles [21]. The list of dams present in Uttarakhand has been represented in Table 1.

District	Name of River	Name of Dam	Latitude	Longitude
Udham Singh Nagar	Baigul and Sukhi	Baigul Dam	28.882112	79.63135
		Baur Dam	29.13048	79.26378
	Kichha	Dhora Dam	28.938466	79.581371
		Haripura Dam	29.044558	79.248097
	Khatima	Nanak Sagar Dam	28.95963	79.89365
	Phika	Tumaria Dam	29.3045	78.9399
Nanital	Baigul and Sukhi	Bhimtal Dam	29.34299	79.56277
	Gola	Jamrani Dam	28.89912	80.20857
Dehradun	Tons	Ichari Dam	30.587172	77.766145
	Yamuna	Lakhwar Dam	30.51795	77.95191
Tehri Garhwal	Bhagirathi	Koteshwar Dam	30.2607	78.50296
	Bhagirathi	Tehri Dam	30.376251	78.435379
Pithoragraph	Dhauli Ganga	Dhauliganga Dam	29.97746	8057651
Uttarkashi	Bhagirathi	Maneri Dam	30.73846	78.53171
Garhwal	Ramganga	Ramganga Dam	29. 51803	78.75832

Table 1: List of dams present in Uttarakhand state of India.

Dams in Himachal Pradesh

Himachal Pradesh, another state in northern India, is known as the "Power state" due to its impressive production of electric energy [22]. The Satluj, Yamuna, Beas, Ravi and Chenab are the main rivers in the state. Table 2 provides a comprehensive list of dams present in Himachal Pradesh.

District	Name of River	Name of Dam	Latitude	Longitude
Bilaspur	Satluj	Bhakra Nangal Project	31.4108	76.4333
		Koldam	32.60996	75.91356
Chamba	Ravi	Chamera – I Project	32.5972	75.985859
		Chamera – II Project	32.5286	76.14429
		Kuther Project	32.2485	76.2756
		Chamera – III Project	32.5286	76.14429
		Bajoli Holi Project	32.28585	76.67906
	Baira	Baira Siul Project	32.8063	76.14178
Kullu	Malana	Malana Project	31.99335	77.46406
	Sorang	Sorang Hydroelectric Project	31.57916	77.86021
	Beas	Largi Hydroelectric Project	31.7196	77.212
	Allain and Duhang	Allain Duhangan Hydroelectric Project	32.22384	77.20523
	Parbati	Parbati III Project	31.7398	77.2576
		Parbati II Project	31.78369	77.33104
Kinnaur	Satluj	Nathpa Jhakri Project	31.56444	77.979993
		Karcham Wangtoo Project	31.54353	78.01783
		Jangi Thopan Project	31.61107	78.43371
	Spiti River	Yang Thang Khab Project	31.26529	79.08214
	Bhabha	Sanjay Vidyut Pariyojna (Bhabha) Project	31.62095	78.021823
	Satluj	Keshang Hydroelectric Project	32.13463	75.689171
Kangra	RanaNerikhad	Uhl III Project	31.87418	76.72959
	Beas	Pong Dam Project	31.9892	76.1081
Mandi	Beas	Dehar Hydroelectric Project	31.42601	76.818756
	Beas	Bassi Hydroelectric Project	31.9546	76.7986
Shimla	Pabbar	Tangnu Romai Hydroelectric Project	31.10461	77.173424
	Satluj	Rampur Project	31.45093	77.630768
Sirmaur	Yamuna	Yamuna Hydroelectric Project	28.06568	79.472217
	Giri	Giri Hydroelectric Project	30.59055	77.6718
Lahul & Spiti	Chenab	Seli Hydroelectric Project	31.81698	77.17423
		Jispa Project	32.63902	77.185181

Table 2: List of dams present in Himachal Pradesh of India.

Dams in Jammu Kashmir

Jammu and Kashmir is a region in northern India that is divided into two main areas: the Jammu area and the Kashmir valley. These regions are separated from each other by Pakistan to the west and the Ladakh region to the east and north. Jammu and Kashmir is reported to produce 10% of the total estimated hydro power potential [23]. Table 3 provides a list of dams present in Jammu and Kashmir, along with their locations.

District	Name of River	Name of Dam	Latitude	Longitude
Kishtwar	Marusudar	Pakal Kul Dam	33.43007	75.86735
	Chenab	Dulhasti Dam	33.36949	75.8007
Ramban	Chenab	Baglihar Dam	33.15599	75.350216
Bandipore	Kishanganga	Kishanganga Dam	34.64981	74.75425
Badgam	Indus	Niu Karewa Storage Yusmarg Dam	33.83216	74.66705
Leh (Ladakh)	Indus	Nimoo Bazgo Dam	34.21534	77.18843
Reasi	Chenab	Salal (Rockfill and Concrete) Dam	33.1436	74.81383
Kathua	Sewa	Sewa St 11 Dam	32.6762	75.8215
Baramula	Jhelum	Uri-11 Dam	34.09225	74.031703

Table 3: List of dams present in Jammu-Kashmir of India.

Effect on River Hydrology

River hydrology refers to the changing volumes of water within fluvial channels. River hydrology is very specific, and the construction of dams has significant impacts on the downstream river flow and channel morphology [24]. Different dams have different impacts on the downstream river flow, depending on their size and function [25]. The construction of dams causes the flow of water to slow down, leading to changes in hydrology [26-33]. This change in hydrology has negative impacts on the ecosystem, as the decreased river flow reduces food chains that are interlinked, thereby disturbing the life cycle of aquatic species.

The storage and redistribution of water in dams and barrages change the natural flows of rivers, which alters the riparian ecosystem [34]. Riparian vegetation provides energy support, habitat design, food sources, and stabilization for aquatic and terrestrial ecosystems [35]. The construction of dams causes the loss of biodiversity of plankton, benthos, and riparian vegetation [36].

Dams also impact the migration rate of fish by decreasing water velocity and turbulence, which are important factors affecting migration rates. In free-flowing water, the migration rate of fish should be high due to high velocity and turbulence, while in the habitat of dam, velocity and turbulence decline, leading to decreased migration rates of fishes [37]. The timing, magnitude, and frequency of water flow are also changed due to damming, which can affect the life cycle of aquatic species [38]. There are three extremely sizable storage dams in the Himachal Alps, namely Bhakra Nangal, Naphtha Jhakri, and Karcham, all of which are on the Satluj river and these dams have very major environmental problems as well as a serious threat to the river hydrology [39].

Effect on Water Quality

The construction of dams and reservoirs has a significant impact on the quality of water in large river systems worldwide, as highlighted in the study by Dynesius M, et al. [12]. Changes in the water quality parameters such as air, temperature, pH, total dissolved solids (TDS), and dissolved oxygen (DO) due to the construction of dams have led to a decline in water quality, which is a major environmental and societal concern [1,8,40-44]. For the aquatic habitats, water self-purification and improvement in water quality are essential for the self sustenense of organisms and ecological repair of the ecosystem [45]. However, the process of self-purification is labile and can be altered due to changing environmental conditions. Construction of dams and reservoirs play a significant factor that affects the environmental conditions of rivers and has a direct impact on water quality and water self-purification.

Water Temperature

The construction of dams leads to an increase in water temperature and nutrients, resulting in eutrophication by algal bloom [46]. The ecological impact of dams on rivers alters the temperature of the water, affecting the health and functioning of aquatic species [47,48]. The release of water from dams plays a crucial role in controlling the downstream temperature [49]. The fluctuation of temperature due to dams affects marine life and pushes them into vulnerable categories. Ramganga reservoir situated at Pauri Garhwal of Uttarakhand which significantly alter the hydrological cycles and hydraulic conditions of the river and alter its thermodynamic state, which alters the river's water temperature [50-52].

pH

The survival of fish species in rivers requires a neutral to slightly alkaline pH, but the construction of dams leads to a decrease in pH downstream [5]. A decrease in pH leads to water acidification, which poses a serious threat to the aquatic diversity in the impounded area [53].

Turbidity

The turbidity of downstream water changes due to the construction of dams, leading to a reduction in water transparency. This obstructs various processes of breeding and feeding. While comparing the turbidity before and after the dams in the Maneri Bhali phase I and phase II built across the Bhagirathi River in Uttarkashi studies, a minor increase was seen. Construction work and mixing of materials water with mud contributed to higher turbidity. Both the NTPC 2011 and NEERI 2011 reports found the same outcome in the same river.

Effect on Aquatic Biodiversity

Aquatic biodiversity is an essential component of the natural environment that provides habitat to a diverse range of organisms. Rivers and lakes are crucial habitats that support numerous aquatic species, and their protection is crucial for maintaining biodiversity. However, the construction of dams has significantly impacted these habitats, resulting in the loss of biodiversity. Dams and reservoirs have significantly altered the aquatic ecosystem, more than any other human activity.

The impact of dams on aquatic biodiversity is a global issue that has drawn significant attention from the scientific community. Several studies have demonstrated that dams have a significant negative impact on aquatic biodiversity, altering the diversity of microorganisms, benthos, plankton, fish, birds, and plants that grow near rivers. The construction of dams has also caused a decrease in the pH levels of water, leading to acidification that poses a threat to the diversity of aquatic systems [53].

Dams have also hindered the migration of fishes by reducing water velocity, affecting the flow of the river, light, temperature, and other environmental factors. These changes lead to slower feeding, migration, and other essential processes. Furthermore, dams have a negative effect on the diversity of benthos, phytoplankton, and zooplankton species, reducing the richness and water fungal biomass in rivers due to flow changes and cooling of water below the dam in downstream reaches [54]. Despite the widespread negative impact of dams on aquatic biodiversity, there is still limited knowledge about the extent of the problem, and effective solutions are yet to be developed.

Phytoplankton

Phytoplankton, which is regarded as primary producers and an indicator of pollution, plays a crucial role in all aquatic systems. The construction of dams can enhance the richness and biomass of phytoplankton. However, the loss of 90% of freshwater flow due to dams can cause the disappearance of plankton biomass and destroy fisheries [55]. Anthropogenic activities can cause an increase in the concentration of nitrogen and phosphorus, leading to changes in phytoplankton's composition and biomass. In contrast, there are no changes in the diversity of plankton caused by silicon. The reduction in silica discharges due to damming can ultimately change the composition of phytoplankton from a diatom-based community to non-siliceous forms (Table 4.1).

Sr. No.	Name of Species	After Dam Construction	Before Construction	Sources
Phytoplankton		Presence/Absence	Presence/Absence	
Bacillariophyceae				
1	Navicula	+++	+++	
2	Cymbella	++	+++	
3	Ditoma	+	+	
4	Meridon	++	+	
5	Syndra	++	+++	
6	Denticula	+	++	
7	Euonotia	++	++	
8	Nistichia	+	++	
9	Crentonies	-	+	
10	Pinnularia	-	+	
11	Gyrosigma	-	+	
12	Hechentia	+	+	
13	Stauriens	-	+	

14	Coconies	-	+	Thapliyal M, et al. [56].
15	Amphora	+	+	
16	Epitima	-	+	
17	Gomphonema	-	+	
18	Fragilaria	-	++	
19	Centorlla	-	+	
Chlorophyceae				
20	Clostrium	+	+	
21	Cosmerium	+	+	
22	Desmidium	+	+	
23	Ulotirix	+	+	
24	Microspora	+	+	
25	Ankistrudemus	-	+	
26	Penium	-	+	
27	Cladophora	-	+	
Myxophyceae				
28	Anabena	+	+	
29	Phormodium	+	+	
30	Ocitierilaria	++	++	
31	Rivularia	+	+	
32	Urenema	-	+	
	Species Richness	19	32	

Table 4.1: Data of phytoplankton of River Ganges pre and post dam wall at ManeriBhali Phase 1 Hydroelectric Project.

Zooplankton

Zooplankton, which is regarded as the primary and secondary link in the food chain and an important component in the water ecosystem. It is a better indicator of eutrophication in aquatic ecosystems. Eutrophication can alter the productivity and structure of freshwater zooplankton.

Benthos

Benthos, which is found on the down side of the river, plays an essential role in the aquatic ecosystem. The construction of dams can change the physical, chemical, and biological nature of downstream regions, affecting the diversity of benthos species. Macroinvertebrate, periphyton, and mussels are the benthos affected by dam construction. Flow alteration due to damming can affect the macroinvertebrates in the downstream region. The species richness of macroinvertebrates before ManeriBhali Dam was 11, but after the construction of dam, it remained only at four [56], (Table 4.2).

Sr. No.	Name of Species	After Dam	Before Dam
		Presence/ Absence	Presence / Absence
1	Crustaceans	+	+
2	Cladocera	++	+
3	Bosmania	+	+
4	Daphnia	+	+
5	Copepod	-	+
6	Cyclops	+	+
7	Diptomus	-	+
8	Rotifera	+	+
9	Kertella	-	+
10	Rotaoria	-	+
11	Nolthoca	-	+
	Species richness	6	11

Table 4.2: Data of macroinvertebrates species before and after the dam at ManeriBhali Phase 1 hydro-electric Power Project [56].

Effect of dams on Fish Diversity

Dams and their construction have been a topic of great concern for the aquatic environment and its inhabitants. The alteration of natural waterways into man-made reservoirs, changes in flow regimes, and habitat fragmentation have significant impacts on the aquatic ecosystem. Among aquatic organisms, fishes are particularly susceptible to these impacts due to their reliance on aquatic environments for their survival. In this research paper, we examine the effects of dam construction on fish diversity with a focus on migration, feeding, and breeding.

Migration

Dams obstruct the natural flow of water and cause delays and blocks in the upstream migration of fishes, leading to a decrease in fish abundance in the river. The efficiency of blocking migration rate varies with the type of dam, with low-head dams having a lower efficiency compared to high-head dams. The effects of dam construction are not limited to local fish populations, as it also prevents the migration of fish species from other regions of the world. The development of a new inter populational structure and the destruction of bidirectional gene flow in fish populations could result from limiting migration pathways, increasing the probability of genetic decline and stochastic extinction [57].

Feeding

Dams have a significant impact on the feeding patterns of fishes by destroying the community of phytoplankton and zooplankton, leading to unavailability of food for fish. The destruction of fish habitat due to river fragmentation also leads to a reduction in fish diversity. Dams alter the composition of phytoplankton by reducing the silica discharges, resulting in a shift from a diatom-based community to non-siliceous forms.

Breeding

The construction of dams and the conversion of lotic water to lentic water affect fish growth and population, leading to an impact on fish breeding. Dams alter the flow of water downstream and disrupt the spawning process by causing a loss of spawning ground. The breeding of many hill stream fish species, such as Schizothorax, sp. Tor sp., Garra sp., Glyptothorax sp., and, is dependent on shallow rocky substrates on river banks. The migration of Tor Putitora in Himachal Pradesh for breeding is impeded by weirs and dams.

Kind of Effects	General Effects	References
Blocking migration route	Have a negative impact on spawning and cause the decreases in abundance and biodiversity of fish and aquatic mammals	Revenga, et al.
Habitat fragmentation	Would cause fragmentation of fish populations, with larger stream fragments supporting larger fish populations which has greater range of fish sizes and higher species diversity	Cooper, et al.
Change from lotic to lentic water in the impounded area	Affects fish growth, population and assemblage structures in the impounded area	Pelicice FM, et al. [58].
Release of hypolimnetic cold water of reservoir	Would delay and reduce upstream migration, inhibit fish spawning and embryonic development, weaken growth and swimming performance, decrease survival of early life stages, and affect fish assemblage structures and biodiversity	Clarkson RW, et al. [59].

Table 4.3: Showing effect of dam and barrages on fishes.

Reservoir in the Indian Himalayan region

Reservoirs in the Indian Himalayan region are crucial sources of water and electricity for a large part of the Indian subcontinent. Two low altitude reservoirs, namely Maharana Pratap Sagar (elevation 436m) and Gobind Sagar Reservoir (elevation 560m), are found in the Himachal Pradesh. Gobind Sagar Reservoir was created in 1963 by impounding the Satluj River with a length of 168 km. This reservoir has the highest sale price value. Pong Reservoir, located on the Beas River, has a surface area of 24,529 ha, a length of 42 km, a breadth of 19 km, and a depth of 35.7 m, and it has the highest per-hectare fish production in the nation [60].

Before the impoundment of the Beas River, the average catch of fisherman per day was low. However, after the reservoir was built, a good income attracted many fishermen who had no other options, with almost 30% of the people living in the catchment region being fishermen. It was discovered that 6284 fishermen in the state made their living exclusively from reservoir fisheries, with a fisherman's average annual income being Rs 96552 in total [61]. The building of the

Gobind sagar and Pong reservoirs has produced an ongoing source of fish for the residents of Himachal Pradesh and the neighbouring states, but migratory species have been severely impacted [62-66].

Conclusion

The construction of dams and barrages in the Indian Himalayan region has significant ecological consequences. This region is known for its rich biodiversity, fragile ecosystems, and the important role it plays in regulating water resources and supporting the livelihoods of local communities. Therefore, any alteration to its natural environment can have profound impacts on both the ecosystem and the people who depend on it.

Given the ecological significance of the Indian Himalayan region, it is crucial to conduct comprehensive environmental impact assessments before the construction of dams and barrages. These assessments should consider the potential long-term consequences on biodiversity, ecosystem services, local communities, and the overall sustainability of the region. Additionally, alternative approaches such as small-scale hydropower projects, decentralized water management, and nature-based solutions should be explored to minimize the ecological footprint of infrastructure development in this fragile and important ecosystem.

Recommendations

When assessing the ecological consequences of dam and barrage construction in the Indian Himalayan Region, it is essential to consider the following recommendations:

- **Conduct Comprehensive Environmental Impact Assessments (EIAs):** Prior to any dam or barrage construction, thorough EIAs should be carried out to assess the potential ecological impacts. These assessments should include a comprehensive study of the biodiversity, hydrology, water quality, soil erosion, and social aspects of the affected areas. The EIAs should be conducted by independent and qualified experts to ensure unbiased results.
- **Implement Mitigation Measures:** Based on the findings of the EIAs, appropriate mitigation measures should be identified and implemented. These measures can include habitat restoration, fish migration pathways, sediment management strategies, and measures to minimize disruption to local communities. The aim should be to minimize the negative impacts and restore ecological functions as much as possible.
- **Promote Sustainable Hydropower Practices:** If hydropower development is deemed necessary, it is important to promote sustainable practices. This can involve implementing technologies and designs that minimize ecological impacts, such as run-of-river projects that minimize the flooding of large areas and prioritize environmental flow releases. Encouraging the use of fish-friendly turbines and incorporating fish passages can help maintain aquatic biodiversity.
- **Consider Alternative Energy Sources:** In addition to hydropower, exploring alternative renewable energy sources like solar and wind can help reduce the pressure on the Himalayan Rivers and minimize ecological disruption. Promoting decentralized energy generation can also help meet local energy needs without large-scale dam constructions.
- **Strengthen Institutional and Legal Frameworks:** Enhancing the institutional and legal frameworks related to dam and barrage construction is crucial. This includes ensuring compliance with environmental regulations, strengthening the capacity of environmental agencies to monitor and enforce environmental safeguards, and promoting transparency and public participation in decision-making processes.
- **Prioritize Cumulative Impact Assessments:** Instead of evaluating each dam and barrage project in isolation, it is important to assess the cumulative impacts of multiple projects within a river basin. Cumulative impact assessments should consider the combined effects on biodiversity, hydrology, and socio-economic aspects. This approach can help identify thresholds and inform more sustainable planning and management strategies.
- **Encourage Public Awareness and Participation:** Creating awareness among the public about the ecological consequences of dam and barrage construction is crucial. Encouraging public participation in decision-making processes and incorporating local knowledge can lead to more informed and sustainable decisions. Engaging with local communities, indigenous groups, and relevant stakeholders throughout the process is essential for addressing concerns, mitigating impacts, and promoting sustainable development.

By implementing these recommendations, it is possible to minimize the ecological consequences of dam and barrage construction in the Indian Himalayan Region, ensuring the long-term sustainability of the region's ecosystems and the well-being of its communities.

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