The Heightened Risk of India's Impetus to Hydropower

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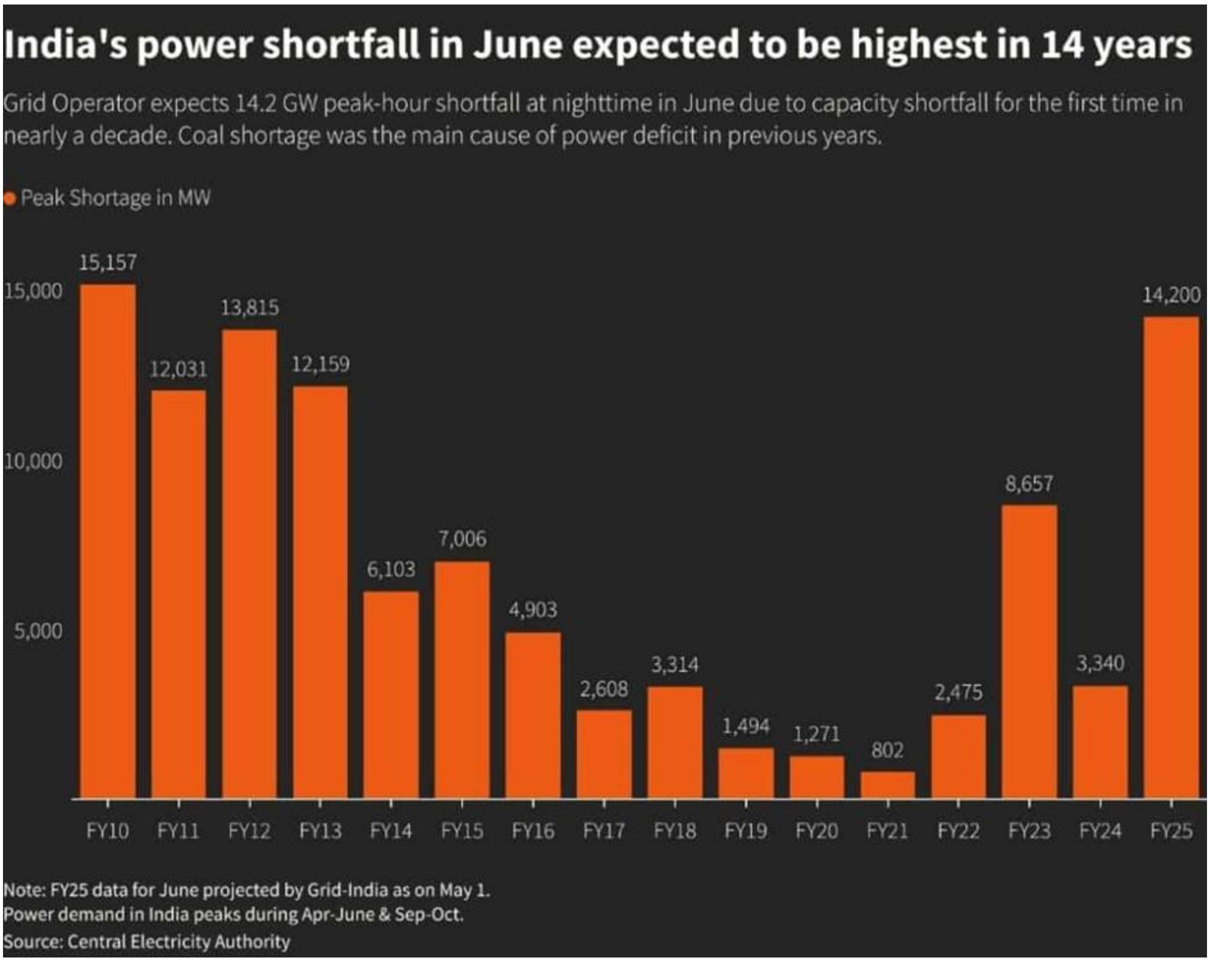
Abstract: ***The current Indian Government's decision to increase investment in development of 31,350 MW hydropower projects to be implemented over the next eight years, has received a mixed response. To promote the hydropower sector and to make it a more viable investment for the private players, the government has declared large hydro projects as renewable energy, is assuring budgetary support for enabling infrastructure, and offering tariff rationalization. The government is also working on a scheme in which developers may receive up to 30% of the project cost as central assistance to further incentivise private investment in setting up of small hydro power plants. Environmentalists have raised the alarm and feel that these decisions need to be taken after due consideration of their ecological and social implications. Yet risks and safety considerations are often being brushed aside for short-term gains. This paper analyses the risks of expanding the hydropower capacity in India that compel caution.***

Keywords: Hydropower, renewable energy, ecosystem, climate change, flash floods, global warming, dams, topography

1. Introduction

With a Gross Domestic Product (GDP) growth of 7% and power demand rising by over 8% this year, India is now the third-largest power market globally, and its energy demand is set to triple by 2050 **[thehindu.com, 2024]**. India is now the third largest energy-consuming country in the world. This is a direct outcome of its rising incomes and improving living standards, after China and the USA. It is estimated that India will soon become the most populated country in the world, adding a city equivalent to the size of Los Angeles to its urban population each year. According to experts, to meet the increase in electricity demand in the next two decades, India needs to add a power system the size of the European Union to what it currently has. India also needs to increase its renewable energy capacity by 4 times by 2030, and make huge investments in strengthening its energy infrastructure, energy storage and energy efficiency **[IEA.org, 2021].** With the fastest and largest urbanization in the world, India's energy demand will increase the most in the world until 2040. According to data, 270 million Indians are expected to migrate to cities in the next 20 years **[Comtois, 2022].** This trend is only going to escalate given the agricultural and rural distress. This surge has created a crisis-like situation. This crisis has the capacity to disrupt normal lives of millions of Indians and poses significant challenges to the nation's economic ambitions. The crisis reached its peak in June 2024 which saw the country's largest energy deficit in 14 years. Furthermore, projections indicate that India could face a significant power shortfall in 2025 and beyond. The country's power demand is growing at a rate of 6% annually and will double by 2045 **[Eric Koons, 2024 in energy tracker].**



Source: Reuters

The growing crisis, evident from the figure above, forced the government India to import coal. It is significant to note that although India is the second largest coal producer, it is also the second largest importer of coal in the world and nearly 17.5% of all coal imports worldwide came from India**[newindianexpress.com].** India's overdependence on fossil fuels, particularly coal and oil, is becoming a liability in the context of climate change demands. Moreover, Coal fired power plants who alone account for over 70% of electricity generation, lead to resource depletion and increasing dependence on imports with volatile prices that can have a negative impact on the country's economy **[Arunoday Mukharji. BBC News].** Moreover, the over dependence on fossil fuels is beginning to have a huge impact on India's carbon footprint. In the last decade India has emerged as the third largest carbon emitter in the world after China and USA, most of which can be attributed to the over-dependence on fossil fuels **[J Clean Prod 2022].** The total annual GHG emissions are projected to reach 2.1 to 2.4 times of present value by 2050 unless concrete steps are taken in time **[Appl Energy 2019].** The impacts of climate change are already visible in terms of frequent floods and heat waves. India has one of the highest populations vulnerable to sea-level rise and many Indian cities are approaching dangerous levels of heat and humidity **[Arun Kumar Dwivedi, Archana Soni 2023].** Some parts of India have seen the world's worst levels of air pollution with the PM2.5 concentration in most of India being ten times higher than the WHO pollution guidelines **[TOI 2025].** According to a World Bank report, "All of India's 1.4 billion people (100% of the country's population) are exposed to unhealthy levels of ambient PM2.5 – the most harmful pollutant - emanating from multiple sources.

This puts India in a precarious position making it urgent for the government to take concrete steps to balance the challenge of limiting the environmental impact of rising population and per capita energy consumption. Consequently, the Indian government is making a significant push to meet 50% of its energy requirements from renewable energy by 2030 and reduce its undue dependence on fossil fuels. A large part of this target has necessitated an increased push hydroelectric power. Hydroelectric power is still considered a preferred option over solar and wind energy for electrical power generation, as are not seen as stable sources for large scale transmission due to their intermittency issue that makes grid integration problematic. Moreover, the exponential cost of storage of solar and wind energy is another factor that makes these two options less popular. Contrarily, Hydroelectric power, is popular for being the more reliable and consistent source. Besides, being comparatively cost effective, it provides the additional benefits of secure irrigation water for agriculture, flood control, tourism etc. It also provides employment and employment opportunities in the remoter areas **[US department of Energy]**. This is extremely significant in India where Agriculture is the mainstay of the rural economy and provides employment for nearly 50% of our population.

It is in these circumstances that the government has taken the decision to increase the hydropower output since the country has tremendous hydropower potential. India is endowed with large hydropower reserves that are estimated to be capable of meeting a demand of around 85 GW at a 60% load factor, making it the fifth in the world in terms of usable hydropower potential **[www.worldenergy.org 2016, pwc.in 2014,17].**

The Government of India has taken various initiatives to harness the hydro-power potential including the hydro pumped storage potential by announcing the flowing incentives to both, states and private investors:

- Declaring large hydropower projects (capacity above 25 MW) as renewable energy source.
- Announcing Hydro Renewable Energy Consumption Obligation by Designated Consumers.
- Conducting Tariff rationalization measures for bringing down hydropower tariff to make projects more economically viable for private investors.
- Offering Budgetary support for Flood Moderation/Storage hydroelectric projects.
- Offering Budgetary support towards cost of enabling infrastructure, i.e. roads, bridges, ropeways, railway siding, communication infrastructure and Transmission Line from powerhouse to the nearest pooling point, including upgradation of polling substations of State or Central Transmission Utility.
- Waiving of Inter State Transmission System (ISTS) charges for hydroelectric projects and PSPs.
- Announcing Central Financial Assistance (CFA) to the State Governments of Northeastern Region (NER) towards their equity participation for development of Hydro Electric Projects in the NER through Joint Venture collaboration between State entities and Central Public Sector Undertakings.
- Reducing timeline by Central Electricity Authority (CEA) for concurrence of Detailed Project Reports (DPR) of hydroelectric projects and PSPs.

Source: Ministry of Power, Dec 2024

Moreover, the government is offering financial assistance and simplifying approval procedures, in an effort to facilitate the rapid advancement of hydroelectric initiatives.

These steps however have been criticised for their lack of regulatory and accountability measures and on the grounds that they don't factor in the ecological risk and the human displacement cost adequately. This paper examines these risks in detail to understand the real human and ecological price attached to this source which needs to be considered before embarking upon a major expansion.

2. Challenges of Hydropower

The Himalayan belt of India with states like Himachal Pradesh which has the Sutlej, Beas, Ravi, and Chenab, Uttarakhand with key River basins like those of the Ganga and its tributaries such as Bhagirathi and Alaknanda, Jammu and Kashmir and Ladakh with vast river networks, including the Indus, Jhelum, and Chenab, Arunachal Pradesh with rivers like the Brahmaputra and its tributaries, which include Subansiri, Lohit, and Siang, Sikkim due to rivers like the Teesta and Rangit and Meghalaya with its heavy rainfall, and several fast-flowing rivers and waterfalls, offer the maximum hydropower potential, which is essential for the country's goal to increase its renewable energy capacity. However, this region also has unique challenges and potential risks, making the process complex and often unsafe. The key challenges that need to be considered o assess long term viability of projects in this region are as follows:

(a) Geological Vulnerabilities

The Himalayan region sits on what is known as the Indus-Yarlung Suture Zone (IYSZ), the line where the Indian and Eurasian plates meet. This zone is under constant stress from the movement of the plates, making it one of the most active earthquake belts in the world **[geolsoc.org.uk].** this zone is prone to earthquakes due to this constant seismic activity. These earthquakes are destructive and leave discernible changes in the topography of the ground surface. Major earthquakes viz. the Chamoli earthquake in 1999, the Kashmir earthquake of 2005, the Sikkim earthquake of 2011, Nepal earthquake of 2015 caused widespread landslides in the Himalayas and massive destruction to life and property **[Pareek et al., 2013, Collins and Jibson, 2015].**

Even the low intensity earthquakes are harmful for the sharp elevated topography and can trigger seismically induced landslides which are more damaging. Studies have revealed that landslides were responsible for approximately 70% of all-earthquake-related casualties that were not caused directly by ground shaking **[Ritu Raj Nath, Naveen Pareek, Mukat Lal Sharma 2022].** Impacts of seismically induced landslides are of long-term nature, manifesting their damage intensity in terms of indirect socio-economic losses **[Journal of Earth System Science,2025].**

Moreover, climate change is impacting weather patterns, melting glaciers and destabilising mountain slopes, adding to the dangers associated with earthquakes in the Himalayas. The melting of thick ice sheets, due to climate change, could reduce load on the earth's crust and this could cause "micro-level earthquakes" (or those with a magnitude less than 3 **[Jacob Koshy, the Hindu 2023]**, enough to cause gradual damage to hydropower infrastructure. The 2021 flash flood in Uttarakhand was caused when a large chunk of a glacier broke off in the Indian state triggering an avalanche rather than an earthquake, damaging an under-construction dam **[theWire.in 2023].**The Himalayas are also warming faster than the global average – in 2022 the Intergovernmental Panel on Climate Change estimates that under a scenario of moderate carbon emissions, Himalayan glaciers would lose 10-30% of their mass by 2030, which itself should be a huge deterrent to building hydropower infrastructure without due diligence. .

Numerous studies have revealed that earthquakes can be induced by human activity, and this has been documented since the 1960s in the case of hydropower dams, because of large reservoirs and what is called reservoir-induced seismicity (RIS). This refers to the pressure created by water in a large reservoir on or near a fault line leading to slippage of the Earth's crust underneath, causing an earthquake **[Joshi, Umesh Raj & Maskey, Ramesh & Kafle, Kumud, 2020].** There are currently about 100 operational hydropower dams across the Himalayan region, with an additional 650 planned or under construction, including in China, India, Pakistan, Nepal, and Bhutan. If all these projects are completed, the Himalayas will become the most dam-dense region in the world, especially in particular areas such as the Chenab region in Jammu and along the Brahmaputra in Arunachal Pradesh [**Li, D., Lu, X., Walling, D.E. et al 2022].**

The 1967 M6.3 Koyna earthquake within about 5 years after the impoundment of Koyna reservoir drew attention of worldwide researchers to understand source mechanism vis-à-vis associated physical processes responsible for genesis of earthquakes in the region. Subsequently, several studies have been carried out in the Koyna-Warna region that has strengthened our understanding of seismotectonic behaviour of the region **[R.K. Chadha et al 2008].** For a long time, the Deccan Volcanic Province was considered non seismic and the incident of 1967, led to deep research on how large reservoirs can trigger earthquakes. The 1967 earthquake, measuring 6.3, was linked to the dam and changed views on reservoir-induced seismicity (RIS). This massive structure was designed to support the Koyna Hydro-Electric Project (KHP), which is the largest hydroelectric power station in India, generating a total capacity of 1,960 megawatts. It is important to note that the Western Ghats are located on the Indian Shield, a more stable part of the Indian tectonic plate. While the Western Ghats can experience earthquakes, they are generally of lower magnitude and less frequent than those in the Himalayas. Some parts of the Western Ghats are classified as Seismic Zone III, indicating moderate seismic activity. On the other hand, the Himalayas are a geologically young mountain range formed by the ongoing collision of the Indian and Eurasian tectonic plates. This collision puts immense pressure on the region, causing frequent earthquakes. The Himalayas are classified as Seismic Zones IV and V, indicating high to very high seismic activity. This comparison in the context of the Koyna incident, itself should make policy makers take steps to expand hydropower more cautiously. While the Koyna Dam stands as a testament to human ingenuity, it also serves as a reminder of the potential risks associated with large-scale engineering projects **[Anup K. Sutar, Sunil Rohilla, Himanshu Chaube, Charulata Chaudhari, 2025].** The Koyna-Warna region in western Maharashtra, India, continues to experience seismic activity, even six decades after the impoundment of Koyna Reservoir serving as a cautious note to overdoing hydropower expansion.

The most recent example of the flash flood in Uttarakhand's Chamoli District in 2021, which ravaged through the valleys of the Rishi Ganga, Dhauliganga and Alaknanda rivers sweeping away the unfinished Tapovan Vishnugad Hydropower Project and inflicted substantial damage on the Rishi Ganga Hydropower Project, is another cautionary red flag. This is in line with the IPCC 2019 report **(Hock et al. 2019)** that cautioned that the mountainous regions susceptible to many cryosphere-related hazards, may witness an increase in frequency and magnitude and areas of these hazards are projected to change as the cryosphere continues to decline.

While this event cannot be directly attributed to climate change, it is well known that climate change can lead to increase in the frequency and severity of mountain hazards **[Krishnan et al. 2019; Vaidya et al. 2019; Hock et al. 2019].** Often these hazards are of a cascading nature with multiple hazards interconnected with a primary hazard trigger and a chain of secondary and tertiary hazards. Human interference in the mountain environment is rapidly increasing. Mountain settlements are increasing in size and land use patterns are changing. Infrastructure such as roads and hydropower projects are rapidly penetrating mountain landscapes. The interplay between natural hazards with human settlements and infrastructure is an important aspect, which can significantly escalate the impacts of event like the Chamoli flood. In the aftermath of recent disaster events, the role of infrastructure, especially hydropower and its interplay with natural hazards has emerged as a topic of strong debate. It has again highlighted that climate change related flow variations, extreme events, erosion and sedimentation, and GLOF/LDOFs, are some of the environmental challenges to hydropower. A comprehensive sustainability framework considering financial, environmental and social sustainability can help make hydropower a viable energy option **[Nie, Y., Pritchard, H.D., Liu, Q. et al. 2021, icimod.org – 2021].**

(b) Environmental Consequences

1) Landslides

The Himalayan region is regarded as the powerhouse of India. To tap this potential, hydropower projects are mushrooming in the Himalayan arc. stretching across till the northeast. The process of building dams in this geologically sensitive region can induce landslides as the region is characterized by steep slopes and fragile geology due to their relatively young geological age. The construction activities associated with dam building and its infrastructural support in terms of road connectivity entails procedures blasting, excavation, and tunnelling which can destabilize these slopes. This infra structural development also includes clearing large swathes of vegetation, which plays a crucial role in stabilizing soil increasing the risk of landslides. During the construction of the Tehri Dam, large areas were deforested, contributing to an increased incidence of landslides in the area. Several villages were devastated by landslides, and later, villagers living above the waters of the newly created lake were found to be living in constant fear of their houses sliding towards the water **[thewire.in 2017]**. Constant movement of Heavy machinery and vehicles add to the reverberations caused by the construction work leading to an increased likelihood of shifts and landslides especially in areas already at risk due to geological instability. It is due to this large-scale construction, that disasters linked to hydropower projects in the Himalayan region have become more frequent in recent years.

Joshimath, in the Indian state of Uttarakhand, that has undergone unplanned construction, drastic road widening and hydropower projects ignoring multiple warnings saw the town sink and majority roads and homes develop cracks due to subsidence. Most blamed the rapid unplanned construction and the ongoing Tapovan Vishnugad hydropower project for their predicament **[dialogue.earth. 2023]**. In 2021, a rock and ice avalanche destroyed the Rishi Ganga project and severely damaged the Vishnugad-Tapovan HEP, leaving over 200 dead, and with estimated losses of Rs 1500 crore. In July 2022, flash floods following a cloudburst in Malana village of Himachal Pradesh's Parvati Valley and another near Choj village damaged the 100 MW Malana II HEP and led to about 5 deaths.

The 2022 compilation report by South Asia Network on Dams River and People Experts shows that hydropower projects act as force multipliers when cloudbursts happen close to them **[downtoearth.org, 2023].** In Arunachal Pradesh, series of disasters marred construction works at the 2,000 MW Lower Subansiri HEP — the largest run-of-the-river hydropower project under construction in the country demanding greater attention to its environmental impact [Upadhyay, R., & Upadhyay, P. 2025]. Dams are also responsible for changes in river morphology and ecology downstream, their nature depending upon characteristics of the original and altered flow regimes and sediment loads. Dams disrupt the continuity of the river system and, especially its sediment load, interrupting the conveyor belt of sediment transport. Dams release sediment-starved, or "hungry water" to downstream reaches, which may transport sand and gravel downstream without replacement from upstream, resulting in coarsening of the surface layer termed 'armouring', which can destabilize slopes Batalla, **[Ramon J. 2003].** Moreover, when a reservoir is filled, the massive body of water exerts pressure on the surrounding land. This additional weight can trigger landslides in unstable areas.

Water seepage from reservoirs into surrounding hillsides can increase pore-water pressure in soils, reducing their cohesion and can trigger a cascade of events resulting in slope instability and landslide occurrences. This process is primarily driven by an increase in soil water content, which therefore reduces shear strength and elevates pore water pressure **[E. Damiano 2019, F. Miao, Y. Wu, Á. Trk, 2023].** The resulting softening of potential sliding surfaces in the soil structure creates conditions conducive to landslide initiation, which can be significantly exacerbated by rainfall **[.P. Ering, G.S. Babu 2016].** Vegetation loss happens when natural vegetation cover on slopes is undercut for efficient transport network for fulfilling the demands of project. This makes landslides worse and they by themselves also loosen the vegetation making the barren cover more dangerous and mobile [biologydiscussion.com]. Thousands of hectares of land are cleared making a loss of precious vegetation cover to construct these dams and its supporting access infra structure.

Examples like the construction of the Koteshwar Dam, a part of the Tehri Dam project in Uttarakhand, and the Karcham Wangtoo Hydroelectric Plant in Kinnaur district in Himachal Pradesh has been linked to increased landslide activity in the vicinity. Residents have reported more frequent landslides following the construction **[india.mongabay.com/2020].**

The Chamoli disaster of 2021 when a large mass of rock and ice from Ronti peak avalanched into the Rishiganga, Dhauliganga and Alaknanda rivers, causing their waters to flood and destroy local dams and villages is a stark warning of how construction of dams in these sensitive areas can compound natural calamities. The scientific community believed that one of the 'features' of the disaster was that it was compounded by large-scale dam construction activities downstream in the Rishiganga river valley: the swelling water toppled concrete and metal structures, and as it raged through the valley building momentum, the debris it carried rendered it more destructive [**science.thewire.in 2022].**

3. Biodiversity Loss

The biodiversity loss from dam construction in the proposed central and the northeastern upper reaches of India has serious consequences. One of the most enormous effects of dams and reservoirs is the transformation of the hydrological regime of the river **[Eng et al., 2013, Zhang et al., 2015].** The reduction in the size of floods below dams affects, inter alia, the reduction of the range of riparian forests and the loss of biodiversity of floodplains [W.L. Graf 1999, and Nislow, 2005]. Dams alter and disrupt the the river flow. Dams interrupt the continuity of sediment transport through rivers systems, causing sediment to accumulate within the reservoir itself and depriving downstream reaches of sediments essential to maintain channel form and to support the riparian ecosystem **[Walling, D. E. (2006].** For example, by constructing the Tehri dam or a hydropower project (e.g. 400 MW Vishnuprayag project on Alaknanda in Chamoli district in Uttarakhand) or on its diversion (Lower Ganga – Bhim Goda at Haridwar, Middle Ganga – Bijnor and Upper Ganga-Narora barrages), we do not leave any water for the downstream stretch of river. So complete drying up of the rivers for most of the dry months by these structures is the first direct impact of these structures on the river. To put it mildly, that action practically kills the river. Upstream of the dam too, the river gets killed, for immediate upstream there is stagnant water, which effects the water quality. Another fall out is that the upstream loses its connections with the downstream river**[https://sandrp.in/2014].** This also causes aquifer depletion and can impact the water supply in the lower regions.

Moreover, the downstream ecosystems suffer from the lack of sedimentation in the water that flows over the dam. Normally, nutrient rich sediment regulates and provides nourishment to downstream habitats. The dams stop this natural sediment flow, and the reduced sedimentation creates less fertile soil, stunting the growth of dependent species. The lack of vegetative growth can lead to erosion and to the destabilization of the surrounding areas **[Earthjustice 2023].**

Downstream habitats are also severely impacted by changes in salinity and oxygen levels. Due to the high rate of evaporation and growth of aquatic vegetation within the reservoir itself, water that travels downstream from a dam usually has a higher salinity content and a lower oxygen concentration than normal **[Jalali, L., Zarei, M., & Gutiérrez, F. 2019].** This change in the chemical makeup of the water creates detrimental conditions for species that previously thrived in those areas and impacts the area that it flows into. Dams even have negative impacts on ecosystems and habitats upstream. Trapped nutrients can facilitate the growth of toxic algae blooms **[Soued, C., Harrison, J. A., Mercier-Blais, S., & Prairie, Y. T. 2022].**

The Sundarbans, the largest remaining areas of mangroves in the world, known for its exceptional level of biodiversity in both the terrestrial and marine environments, including significant populations of globally endangered cat species, such as the Royal Bengal Tiger acquires freshwater discharge typically from the flow of the Ganges River **[Rahman et al., 2017]** and is a fine example of how man- made changes can impact a resilient ecosystem. The development of the Farakka Dam in 1975 altered stream hydrology significantly and has since stunted the growth of the islands as a result of the sediments that the dam keeps back. This will lead to increasing risks to both the health of the mangrove forest and the human population as sea levels rise and the severity and strength of tropical storms intensify as a result of climate change **[internationalrivers.org].**

The NE India is included in two global biodiversity hotspot areas: Eastern Himalaya and Indo-Burma **[Myers et al., 2000; Mittermeier et al., 2011].** The project site of the LSHEP and its submergence areas of 4030 hectare are parts of evergreen forest tracts of the Eastern Himalaya biodiversity hotspot **[Choudhury 2013].** These forests are home to several IUCN red listed fauna, including Endangered species such as Bengal tiger, Dhole, Bengal slow loris, Fishing cat, Black musk deer, Hog deer, etc.; and 'Vulnerable' species include Asiatic black bear, leopard, clouded leopard, Gaur, Capped langur, Binturong, Sambar, Takin, etc. Some of the other threatened animals found here are Marbled cat, golden cat, Assamese macaque, Large Indian civet, Malayan giant squirrel, etc. **[Choudhury 2013, 2016, 2018]**. The submergence area is a critical habitat of several threatened and endemic amphibian and reptilian species **[Ahmed et al., 2009; Varadaraju 2018].** The submergence area is a part of the 'Subansiri Important Bird area' and thus avifauna of the area is also promisingly diverse, some of which are Rufous-necked Hornbill (Vulnerable), Steppe eagle (Endangered), Himalayan vulture (Near threatened), Blyth's Tragopan (Vulnerable), Great Hornbill (Vulnerable), Bengal florican (Critically Endangered) (Choudhury 1998), White-winged wood duck (Endangered), etc. **[Choudhury 1996, 1997, 1998, 2007].** All these animals are protected in India under Wildlife (Protection) Act, 1972.

Dr. Anwaruddin Choudhury, an eminent naturalist of NE India, reported that the forest area along the border of Assam and Arunachal Pradesh, including the project site of LSHEP, is a part of the contiguous habitat of the Endangered Asiatic elephant **[Choudhury 1999, 2004; Williams et al., 2020].** The Subansiri river is an important habitat of the Endangered Ganges River dolphin **[Anderson 1879; Wakid et al. 2010],** which is the state aquatic animal of Assam, and national aquatic animal of India **[Mazumder et al., 2014].** The dolphin inhabiting section of Subansiri river is just 12 km downstream of the project site. Thus, the project-induced altered flow regimes would make the upstream reaches shallow thereby devastating their habitat and extirpate the entire resident dolphin population **[Baruah et al. 2012; Wakid et al. 2010].** In addition, researchers have reported over 204 species of fishes from the lower Subansiri river, including Golden mahseer - an Endangered migratory fish species **[Das et al. 2013; Bakalial et al. 2014]**. Similar impacts of dams and barrages on aquatic life and the dolphin has been surmised from the Barak **[Choudhury et al. 2019]** and the Ganges River (Sinha and Kannan 2014). Since the Subansiri river contributes about 10% of the flow of the Brahmaputra River, the dam-induced altered flow regimes would also affect the dolphins and other aquatic life in the Brahmaputra River substantially **[Goyal et al. 2018].**

For the construction of the LSHEP, a large stone quarry has been set up on the downstream river bank (Fig. 4B). Furthermore, quarrying of boulders and sand has resulted in disturbances in the river, affecting siltation, sedimentation, and aquatic bottom fauna. These activities of the dam developers are in violation of the 2004 verdict of the honorable Supreme Court of India. In addition, about 70 km of road has been constructed so far, and about 1500 workers are currently working at the project site. During the construction, a large tract of the forest has already been cleared, and the commissioning of the dam would submerge another huge chunk of primary forest [**Vagholikar and Ahmed 2003].**

In addition to the aquatic life, the downstream valley of the Subansiri river is home to some of the splendid wildlife species, including Bengal florican (Critically Endangered), Asiatic wild water buffalo (Endangered), Asiatic elephant, the Great Indian One-horned rhino (Vulnerable), etc. **[Choudhury 2013, 2018].** Some of the noteworthy avifauna found here includes 'Critically Endangered' species like Oriental White-backed vulture; 'Endangered' species like Greater Adjutant stork, and migratory birds, including Bar-headed goose, Ruddy Shelduck, Gadwall, Mallard, Eurasian Wigeon, Red-crested Pochard, Common Pochard, Tufted duck, Ferruginous duck, Great crested Grebe, Black Stork, Great Cormorant, Common Kestrel, Peregrine Falcon, Black-eared Kite, Osprey, Himalayan Vulture, Griffon Vulture, Eurasian Marsh Harrier, Pied Harrier, Northern Lapwing, Grey-headed Lapwing, Pacific Golden Plover, Common Sandpiper, etc. [**Choudhury 2000; Grimmett et al., 2011].**

The Subansiri is an interlaced river, and forms a large number of Chapories (riverine islets, sandbars and tracts) during lean season, while several of them are perennial. These Chapories are the lifeline for several wildlife species, providing refuge, and grazing and nesting grounds **[Choudhury 2013].** The presence of the dam will threaten this entire natural ecosystem and hydrology impacting the precious biodiversity of this region.

Another example is the impact of building dams on the Bhagirathi and Ganga rivers. These dams create obstructions across rivers inhibiting the migration of fish and other aquatic species leading to the isolation of habitats, which can affect the genetic structure of populations. Studies have shown that these golden mahseer in these rivers are an essential part of the conservation plan to maintain the genetic diversity within the basin **[india.mongabay.com/2020].** Found in cold-water habitats of the Himalayan region, the presence of the endangered golden mahseer, a flagship species, indicates healthy freshwater ecosystems. The fish is very sensitive to change in water temperature; therefore, small climatic fluctuation may lead to a change in its genetic structure. Dams and barrages across rivers disrupt 'longitudinal connectivity' or the free flow of water, sediment, and organisms. These barriers limit the dispersal of species and create isolated microhabitats. Previous studies have shown that the barrier effect caused by Tehri dam, located at the confluence of Bhagirathi and Bhilangana, has resulted in a decline in the populations of mahseer upstream of Bhagirathi River, according to a 2012 WII report **[indiawaterportal.org].**

These are just few instances to point out the loss that needs to be considered seriously.

4. Sediment starvation and Geomorphic Collapse

Globally, it was always acknowledged that dams could play a crucial role in flood control by holding on to sediments that could play havoc downstream. However recent instances have created doubts about this claim making it extremely important for Governments to make a more thorough assessment before expanding the Dam network in haste. It is evident that dams in the Himalayas have strongly impacted the river system management, impeding not only the movement of river flows but also the delivery of sediments downstream creating geomorphic disconnectivity in the channels. Numerous studies have demonstrated the relevance of the changes in sediment load and the degree of river disconnectivity through geomorphological Beld observations **[Jain and Tandon 2010; Singh and Sinha 2019; Yang et al. 2019].** It cannot be overlooked that the Himalayas are susceptible to hazards mainly because of its rugged topography, high relief, rainfall distribution, lithology, and complex geological structures, where any extreme event like high-intensity rainfall, Cash Coods, glacial lake outburst Coods (GLOFs), landslide lake outburst Coods (LLOFs) and an earthquake that can trigger landscape changes **[Wasson et al. 2013a, b; Ziegler et al. 2014; Veh et al. 2019; Panda et al. 2020; Sharma et al. 2021].**

The Uttarakhand disaster of 2013, a cloudburst-driven lake breach event is considered as the largest hydrological extreme in the past millennium **[Wasson et al. 2013a, b].** The event resulted in devastating floods and landslides, discharging a huge quantity of water and sediments downstream into the river leading to massive loss of life and economy **[Chahal et al. 2017].** Studies have shown that a river carves its channel size naturally, construction of dams on them changes the volume of waters and sediment. This excessive sediment/water bulks the riverbed and modifies the channel morphology significantly. The magnitude of these changes depends upon the channel gradient and the geology that the channel traverses. The sediment–water routing during such large-scale events as it interacts with the geology of the mountain often leads to changes in riverbed elevation, planform, and active channel width that may remain transient for decades or may get overprinted with subsequent events **[Wasson et al. 2013a, b].**

During the 2013 event, the muck of the Srinagar hydro project played a negative role and damaged lower Srinagar**.** The Srinagar Hydropower projects (height and capacity of dam are 90 m and 330 MW, respectively, and the storage capacity of reservoir is 3.63 million cubic meters) blocked the connectivity of the river channel and arrested the bedload significantly in the reservoir upstream and obstructed the flow of sediment to downstream reaches. **Sundriyal et al. (2015)** infer that during the peak of 2013 flood, dam's gates were opened that spilled the suspended load in the downstream which contributed to raising the riverbed locally during the flood significantly, and as a result, the floodwaters of 2013 achieved flood levels that were 3–4 m higher than that of 1970 floods. Many studies in the area after the disaster showed that the stored muck released by the dam bulked the river in the vicinity of dam in downstream, reflected in the form of increased aggradation. This suggests that the reservoir actually added to woes in terms of long-term natural ways of sediment transfer in the channel, worsening the tragedy.

Himalayan states, being geodynamically active, are susceptible to natural hazards and underscore the importance of the criticality of site selection for the construction of dams. A significant number of dam failures are reported, and their being is questioned **[Lwarkha et al. 2020; Srivastava et al. 2021].** Considering the recent extreme event in Rishiganga **[Rana et al. 2021; Shugar et al. 2021]** and the failure of Vishnugad hydro project to cope with the risk reflects the poor knowledge of potential site selection for dam construction **[Kumar et al. 2021].** The Himalayan rivers inherently transport exceptionally large amount of sediment due to the glaciers in their headwaters, during extreme hydrometeorological events this moves down and when this combines with the held-up sediment load in the dam during heavy rains, it can be catastrophic. Thus, it is important to understand the consequences of dam construction on the geomorphic connectivity and its potential damage to the ecosystem. Dams that cause channel disconnectivity or any other engineering intervention that does not allow effective sediment transfer should be avoided.

More than 80% of the total hydro potential of the country lies in the western Himalayan states (Jammu and Kashmir, Himachal Pradesh, Uttarakhand and Arunachal Pradesh **[Sharma and Thakur 2016].** These are areas where flood waters provide overwhelmingly high thrust to dams due to high gradients, stream power, and availability of large amount of sediments that lead to failures and loss of life and property repeatedly. This risk cannot be ignored due to change in precipitation patters owing to climate change.

Disasters linked to hydropower projects in the Himalayan region have become more frequent in recent years. The latest example of this can be seen in Uttarakhand's Joshimath town, where more than 800 buildings have developed cracks due to subsidence. One of the reasons for this was the ongoing Tapovan Vishnugad hydropower project.

In 2021, a rock and ice avalanche destroyed the Rishi Ganga project and severely damaged the Vishnugad-Tapovan HEP, leaving over 200 dead, and with estimated losses of Rs 1500 crore. In July 2022, flash floods following a cloudburst in Malana village of Himachal Pradesh's Parvati Valley and another near Choj village damaged the 100 MW Malana II HEP and led to about 5 deaths. The 2022 compilation report by South Asia Network on Dams River and People Experts shows that hydropower projects act as force multipliers when cloudbursts happen close to them **[downtoearth.org 2023].**

Moreover, the Himalayan Rivers are considered a lifeline for billions of people, providing drinking water and supplying sediment nutrients for food production in the region (NRC, 2012). During dam construction, sediment yields may change **[Magilligan et al., 2021, R. Sinha et al. 2019, A. Das et al. 2017, K Ghosh 2022],** affecting ecosystems and livelihoods downstream as the plains that rely on these sediments for their fertility may lose out.

4.1 Emission of greenhouse gases

Hydropower is traditionally regarded as a low-carbon energy source. However, some studies have suggested that hydropower production could potentially release more GHG emissions than fossil fuel energy from a life cycle perspective, especially considering the large amount of methane emitted from flooded biomass **[P. Denholm et al. 2004, Varun et al 2012, S. Zhang et al 2015].**

Dams emit greenhouse gases (GHGs) primarily from the decomposition of flooded organic matter in reservoirs, a process that releases methane and carbon dioxide. These gases then escape into the atmosphere through various pathways, including diffusion, bubbles (ebullition), and degassing when water passes through turbines **[US Department of Energy].**

Steinhurst et al estimated that tropical reservoir-based dams could emit 1300–3000 g CO_2 eq./kW h, compared to 400–500, 790–900, and 900–1200 g CO_2 eq./kW h for thermoelectric plants using natural gas, oil, and coal, respectively. Similarly, **Fearnside (2015)** compared the hydropower generated from the Petit Sau (French Guiana) with electricity generated from combined-cycle natural gas and found that the GHG emissions from the dam are 19 times higher than the natural-gas-based electricity. These contradictory conclusions of dam GHG emissions reflect our limited understanding of the overall sustainability of hydroelectric dams and the associated implications on the optimal design and operation of these dams.

These findings exhibit that the lack of consistent long-term research about reservoir-based GHG emissions in many areas of the world is a major obstacle towards achieving an accurate global estimate **[Dos Santos, Marco & Rosa, Luiz. 2011].**

Rivers when unfettered and healthy help regulate an increasingly volatile global carbon cycle by drawing an estimated 200 million tons of carbon out of the atmosphere each year. This is just one of the dozens of essential services provided by free-flowing freshwater ecosystems, which range from provision of food to flood mitigation and access to water supply **[https://www.whoi.edu/press-room 2015].**

4.2 Social and economic implications

Construction of dams in the Himalayas and Northeast India has significant impacts on both livelihoods and social structures in these regions. This impact assumes greater complexity as these regions have unique ecological, cultural, and socio-economic characteristics. Large dam projects often result in the of vast tracts of land, leading to the displacement of local communities and impacting their livelihoods as most indigenous people of these communities rely heavily on agriculture, forestry, and fisheries for their livelihood. Lack of adequate arrangements for their resettlement that can ensure an equivalent or better living conditions and employment opportunities, make these people extremely vulnerable economically and socially. Moreover, most of these indigenous communities have very strong cultural and spiritual connections to their land and rivers. This is stronger as before the infrastructural development associated with Dam construction, most of these communities lived an isolated existence with very little exposure to the rest of the country and the world. Displacement makes them fear the loss of cultural heritage, traditional knowledge, and social cohesion as people are displaced and dispersed.

Moreover, the decision-making processes surrounding dam construction often excludes local communities. This builds a feeling of disenfranchisement and mistrust in governmental authorities. Lack of participation can undermine community empowerment and resilience. The protest movement against the Tipaimukh dam, Pagladiya dam, Siang dam and the Subansiri dam are some of the examples of grassroots movements against mega hydropower projects in the Northeastern region **[Hussain 2008: 101].** These protests against the mega dam projects in Northeast India highlight the issues related to land acquisition, compensation, resettlement as well as rehabilitation for displaced and project-affected people. This includes, among other things, the issues of Internally Displaced People (IDP). Loss of traditional means of livelihood and community networks and the fear of the possible collapse of the dam due to natural calamities have undermined their cultural rights as well as their right to life. The issues of resettlement and rehabilitation have pitched the policymakers, and even the government against its own citizens. Large hydro projects in India have been resisted on environmental grounds, and for violating human rights. The citizens of the region have organised movements against the state-sponsored mega dams, because these projects are responsible for both physical displacement and livelihood displacement. The protest movement against the Tipaimukh dam, Pagladiya dam, Siang dam and the Subansiri dam are some of the examples of grassroots movements against mega hydropower projects in the Northeastern region (**Hussain 2008: 101**). People are also protesting the perceived threat of the dam collapsing because of natural calamities like earthquakes as the area is seismically sensitive and vulnerable to floods and landslides. There is also growing rivalry between the protests in assam and Arunachal Pradesh over the issue of power sharing which is an integral aspect of politics of big dams, which are located in more than one state [Kaushik Deka 2010].

According to the project authorities the lower Subansiri dam dam will submerge the agricultural lands of two villages, Gengi and Siberite. The families to be affected belong to the Gallong tribe, a subgroup of the Adis. These are agricultural communities practicing jhum cultivation, terrace rice cultivation and wet rice cultivation near the riverbed. Besides they also depend on forest for their livelihood. So, all these resources will no longer be available once they are displaced. Although they were promised housing and homestead land, cultivable land (one hectare), civic amenities, schools and vocational training in animal husbandry, horticulture, weaving and other activities, there have been differences in what was promised and what has been delivered. Like Subansiri, Tipaimukh hydroelectric project also has been the bone of contention between the government and the affected people. The project will submerge the national highway no. 53, the only alternative to Imphal Dimapur lifeline (NH No.39). Hence new alignment of the submergible points on the road will add a distance of another 60 kms to the existing Imphal-Jiribam-Silchar road. Though Manipur and Mizoram

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have been promised 12 percent of the output as royalty, the critics have long been warning that the dangers far outnumber the potential benefits. For instance, the Naga leaders claimed that the dam would submerge the socially and economically important places. The site chosen for the dam on the Tuivai river was also prone to intense seismic activity. The dam will also submerge various historical and legendary sites and sacred groves with vital spiritual and cultural significance to the communities and lead to destruction of rich biodiversity which is threatening the peoples' right to life and livelihood. Like other development projects in the northeast, here too, the people that are most adversely affected are tribes: the Zeliangrong a constituent of three Naga tribes and the Hmar will be the direct victims of the project **[Linda Chhakchhuak, 2006, Arora, V. and Kipgen, N. 2012].**

The Loktak project is another example of how the local communities were impacted. The wetlands known for their socio-economic significance and rich cultural heritage but has been decimated by the construction of the contentious and controversial 105 MW Loktak Multipurpose Hydroelectric Project (Loktak HEP). For generations, the people of Manipur, the Meitei, Nagas and Kukis, lived in close proximity to the oscillating flow of the wetlands and depended on them for their livelihoods. According to Meitei folklore, Loktak is home to the revered mythical horned python called Poubi Lai, which exhibits its cutlral significance for the communities. The same Local communities were dealt a further blow when the Manipur Loktak Lake Protection Act (LPA) was promulgated in 2006 to ensure an uninterrupted water flow for the Leimatak Power Station under the pretext of protecting the wetlands. The law divided the wetlands into zones that prohibits various activities, including fishing and waste disposal, that undermines the community's human rights. The Loktak HEP caused massive displacement of the Meitei people of Manipur. Many families were banished with no compensation, resettlement or rehabilitation plan in place. The communities had no choice. In November 2011, nearly 700 phumshang or floating huts were burnt down by the government, affecting more than 3,000 people, and many women from Langol Shabi and Nambul Machin areas. Even those who chose to stay face bleak prospects.

An estimated 83,450 hectares of agricultural lands on both sides of Ithai Dam has been affected. Paddy fields and natural fisheries which have been in existence for hundreds of years, sustaining families for generations, have been submerged, directly affecting more than 100,000 individuals, mainly of the Meitei community. Once self-sufficient, Manipur now imports food. The impact on the lives of local communities and women in Loktak and the surrounding areas have been severe. Women cannot fish or collect edible plants, or trade their goods at the market, anymore. They are also not able to keep their cows and buffaloes, since this land is now submerged. The impact of the Ithai Barrage and the Loktak HEP goes far beyond the Loktak Wetlands. It's even called local traditional earthen pottery works as the the sudden release of water from the barrage and the deposition of sediments in the repeated flooding has covered the area where villagers collect the earth suitable for pottery **[www.internationalrivers.org 2021].**

It's no different in the upper north areas. The Srinagar Dam, with a capacity of 330 MW, spans from Kaliyasaur to Srinagar, covering a 16-kilometer stretch of the Alaknanda River was commissioned in 2014. It submerged vast tracts of agricultural land, forests, and human settlements, affecting both the natural landscape and the livelihoods of local communities **[Rawat GS, Adhikari BS 2016]**. The dam's construction has led to the submergence of over 1900 hectares of land, including 339 hectares of forest area, which has significant implications for biodiversity and ecosystem services in the region **(Draft 12th Five Year Plan, 2012-2017).** The socio-economic impact of the Srinagar Dam is equally profound. The dam has led to the displacement of communities, loss of agricultural land, and changes in traditional livelihoods. Villages such as Dhari, Barkot, and Koteshwar, among others, have been particularly affected, with many residents forced to relocate due to the reservoir's rising waters **[Saxena R, Gupta S 2017].** The socio-cultural fabric of the region has been disrupted, with long-standing practices of agriculture and animal husbandry giving way to new forms of livelihood, often linked to the burgeoning tourism industry that the dam has inadvertently fostered **[Pant R, Agarwal M, Juyal N 2019, Bisht M, Joshi RK 2020, Singh S, Rawat R 2021].** These examples emphasise the fact that the governments must also take into account the socio – economic fallout of dam building and not treat the matter unconcernedly.

5. Conclusion

India's economic growth, urbanization, industrialization and population explosion in the last decades has increased the demand for power supply substantially. At the same time there is tremendous global pressure on India for reducing carbon emission which has diverted the focus towards greener energy sources, including hydropower **[Moran *et al.*, 2018; Choudhury and Dey Choudhury 2020a].**

Chasing ambitious goals, the Government of India is moving rather swiftly with its plans to expand dams across the Himalayas with more emphasis on the Northeast and Kashmir. The government and proponents of large dams in the region paint a win-win picture: exploiting the country's largest perennial water system to produce cheap, plentiful power for the nation, economic benefits through power export, employment generation, the end of militancy, flood control and little direct 'displacement' of local communities. Dams are made out to be the panacea for all the problems of the northeast **[Kohli, Kanchi. 2003].**

Lessons from past dams and the impact it has on the local ecosystem are often overlooked to exploit the situation. The fallout of existing dams shows that there is very little fact finding and groundwork done. Moreover, legal violations by project authorities, lack of transparency and little scope for effective people's participation in decision-making only worsens the situation. It would be better if the governments take a more cautious approach keeping in mind the warning of the World Commission on Dams (WCD)12 established by the World Bank and the International Union for the Conservation of Nature, as early as in May 1998 in response to the large dam debate. The first independent assessment of dams report concluded that "while dams have made an important contribution to human development and benefits derived from them have been considerable, in too many cases an unacceptable and often unnecessary price has been paid to secure those benefits, especially in social and environmental terms, by people displaced, by communities downstream, by taxpayers and the natural environment **[WCD, November 2000]**." The last quarter of the 20th century saw a gradual shift in opinion with reference to large dams. Globally, the construction of new dams has fallen by 60% since the 1970s. Additionally, dams which do not serve their purpose or are too expensive to maintain are being decommissioned and there is an increasing momentum towards river restoration. Even the argument that hydro power is a clean energy option has been dispelled as reservoirs have been found to emit greenhouse gases.

Thus, it is significant to note that while the dam construction has been reduced in developed economies, the developing ones like India are powering ahead without learning from the lessons of the past. Hydropower comes with enormous, irreparable and permanent damages to the environment [**Tortajada *et al*., 2012; Moran *et al.*, 2018].** Altered flow of rivers has ecological and hydrological impacts and leads to loss of biodiversity (Bunn and Arthington 2002; Petts and Gurnell 2005). Globally, dams have displaced over 80 million people, and the figure in India is between 16-38 million **(WCD 2000)** and likely to rise with the increase in dam construction activity in areas like Arunachal and Kashmir. **Scudder (2012)** has reported that the socio- economic status of over 82% of these displaced people deteriorated in dam areas/ the situation is reported to be no different in India. In the past six years, from 2016-17 to 2021-22, India's large hydropower projects have contributed just around 10 per cent of the total power generation, going as low as 9.68 per cent in 2017-18.In three of these six years, large hydropower projects contributed less than 10 per cent, recovering only marginally in the rest of the years, thanks to surplus monsoon, says another analysis on power generation by hydropower projects by SANDRP, released in November 2022 **[www.downtoearth.org.in].** These statistics warrant a more deliberate discussion on the long-term viability of these projects' vis a vis their environmental and socio-economic impact on the local population.

India cannot afford to ignore the ensuing global warming and climate change and its impact on the food and water security of its people. In such a juncture, it is the need of the hour that the water, land and biological resources are conserved, managed and utilized in a sustainable manner **[Misra 2014; Ostad-Ali-Askar et al. 2018; Javadinejad et al. 2021; Talebmorad et al. 2021].** Thus, rather than exploiting the freshwater resources, like rivers, for economic growth, focus should be diverted to their conservation necessitating a more cautionary and consultative approach involving all stake holders and the local population.

References

[1] https://www.thehindu.com/business/indias-energy-demand-to-triple-by-2050/article68719527.ece
[2] IEA.org (2021). India Energy Outlook 2021. Retrieved from https://www.iea.org/reports/india-energy-outlook-2021. Accessed on 16.07.2022.
[3] Comtois J. (2022). India Projected to Become World's Most Populous Country. Retrieved from https://etfdb.com/emerging-markets-channel/india-projected-to-become-world-s-most-populous-country/#:~:text=India%20is%20projected%20to%20become,World%20Population%20Prospects%202022%20report. Accessed on 21.07.2022.
[4] https://energytracker.asia/energy-crisis-in-india-what-is-next/
[5] https://www.reuters.com/business/energy/india-projects-biggest-power-shortfall-14-years-june-2024-05-09/
[6] https://www.newindianexpress.com/business/2023/Mar/14/india-imported-186-mt-coal-in-fy23-govt-data-2555901.html
[7] https://www.bbc.com/news/business-58824804, Why India is on the brink of an unprecedented power crisis, 11 October 2021, Arunoday Mukharji, BBC News, Delhi
[8] Initiatives to Harness Hydro Potential https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=2079832
[9] Forecasting of future greenhouse gas emission trajectory for India using energy and economic indexes with various metaheuristic algorithms, J Clean Prod (2022)
[10] J. Jiang et al.Research on the peak of CO_2 emissions in the developing world: current progress and future prospect- Appl Energy(Feb. 2019)
[11] Arun Kumar Dwivedi, Archana Soni, The carbon footprint of India and its drivers: A structural decomposition analysis of global value chains, Sustainable Energy Technologies and Assessments, Volume 56,2023,103109,ISSN 2213-1388, https://doi.org/10.1016/j.seta.2023.103109.
[12] http://timesofindia.indiatimes.com/articleshow/118876515.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst
[13] https://www.energy.gov/eere/water/benefits-hydropower
[14] World Energy Council. (2016). World Energy Resources 2016. Retrieved from www.worldenergy.org/wp
[15] https://www.pwc.in/assets/pdfs/publications/2017/accelerating-hydropower-development-in-india-for-sustainable-energy-security.pdf
[16] https://www.geolsoc.org.uk/Plate-Tectonics/Chap3-Plate Margins/Convergent/Continental-Collision.html
[17] N. Pareek et al.Study of effect of seismic displacements on landslide susceptibility zonation (LSZ) in Garhwal Himalayan region of India using GIS and remote sensing techniques
[18] Collins, B.D., Jibson, R.W., 2015. Assessment of Existing and Potential Landslide Hazards
[19] Ritu Raj Nath, Naveen Pareek, Mukat Lal Sharma, Implications and inclusion of size-dependent scenario earthquakes on landslide hazard zonation: A case study of the Indian Himalayas, CATENA, Volume 212,2022,106027, ISSN 0341-8162, https://doi.org/10.1016/j.catena.2022.106027.
[20] Earthquake-induced landslide hazard assessment using ground motion parameters: A case study for Bhagirathi

Valley, Uttarakhand, India 2025, Journal of Earth System Science

[21] https://www.thehindu.com/news/national/climate-change-may-have-increased-frequency-of-earthquakes-in-himalayas-says-minister-of-earth-sciences/article66706941.ece

[22] https://science.thewire.in/environment/explained-climate-change-earthquakes-hydropower-himalayas/#:~:text=Another%20way%20in%20which%20climate,%2C%20is%20more%20than%20ever.%E2%80%9D

[23] Joshi, Umesh Raj & Maskey, Ramesh & Kafle, Kumud. (2020). A Review on the Mechanism of Reservoir-Induced Seismicity for Nepalese Context. Nepal Journal of Science and Technology. 19. 215-221. 10.3126/njst.v19i1.29823.

[24] Li, D., Lu, X., Walling, D.E. et al. High Mountain Asia hydropower systems threatened by climate-driven landscape instability. Nat. Geosci. 15, 520–530 (2022). https://doi.org/10.1038/s41561-022-00953-y

[25] R.K. Chadha et al. Reservoir triggered seismicity (RTS) and well water level response in the Koyna-Warna region, India, Tectonophysics. (2008)

[26] H.K. Gupta, Short-term earthquake forecasting maybe feasible at Koyna, India, Tectonophysics, (2001)

[27] H.K. Gupta, A review of artificial reservoir triggered earthquakes with special emphasis on earthquakes in Koyna, India. Earth-Sci. Rev.(2002)

[28] A.P. Pandey et al.Surface loading and triggering earthquakes in the Koyna–Warna region, Western India, Phys. Earth Planet. Inter. (2003)

[29] N.P. Rao et al, Periodic variation of stress field in the Koyna–Warna reservoir triggered seismic zone inferred from focal mechanism studies, Tectonophysics (2016)

[30] S.V.S. Sarma et al.A magnetotelluric (MT) study across the Koyna seismic zone, western India: evidence for block structure, Phys. Earth Planet. Inter. (2004)

[31] R.K. Chadha et al.Reservoir triggered seismicity (RTS) and well water level response in the Koyna-Warna region, India Tectonophysics. (2008)

[32] H.K. Gupta -A review of artificial reservoir triggered earthquakes with special emphasis on earthquakes in Koyna, India.Earth-Sci. Rev. (2002)

[33] N.P. Rao et al. Periodic variation of stress field in the Koyna–Warna reservoir triggered seismic zone inferred from focal mechanism studies, Tectonophysics (2016)

[34] Anup K. Sutar, Sunil Rohilla, Himanshu Chaube, Charulata Chaudhari, Revisiting the reservoir-triggered seismicity of Koyna India using near-source seismological observations and relationship with reservoir water level changes, Tectonophysics, Volume 907, 2025, 230743, ISSN 0040-1951

[35] Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., Steltzer, H.I. (2019). Chapter 2: High Mountain Areas. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, in: Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N.M. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. pp. 131–202.

[36] Krishnan, R., A. B. Shrestha, G. Ren, R. Rajbhandari, S. Saeed, J. Sanjay, M. A. Syed, R. Vellore, Y. Xu, Q. You, and Y. Ren (2019). Unravelling Climate Change in the Hindu Kush Himalaya: Rapid Warming in the Mountains and Increasing Extremes. The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People, P. Wester, A. Mishra, A. Mukherji, and A. B. Shrestha (Eds.), Springer International Publishing, 57-97. https://doi.org/10.1007/978-3-319-92288-1

[37] Vaidya, R. A., M. S. Shrestha, N. Nasab, D. R. Gurung, N. Kozo, N. S. Pradhan, and R. J. Wasson (2019). Disaster Risk Reduction and Building Resilience in the Hindu Kush Himalaya. The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People, P. Wester, A. Mishra, A. Mukherji, and A. B. Shrestha (Eds.), Springer International Publishing, 389-419.

[38] Nie, Y., Pritchard, H.D., Liu, Q. et al. (2021). Glacial change and hydrological implications in the Himalaya and Karakoram. Nat Rev Earth Environ 2, 91–106. https://doi.org/10.1038/s43017-020-00124-w

[39] https://www.icimod.org/article/understanding-the-chamoli-flood-cause-process-impacts-and-context-of-rapid-infrastructure-development/

[40] Z. Zhang et al.Hydrologic alteration associated with dam construction in a medium-sized coastal watershed of Southeast China, Water(2016)

[41] K. Eng et al. River flow changes related to land and water management practices across the conterminous United States- Sci. Total Environ.(2013)

[42] W.L. Graf -Dam nation: a geographic census of American dams and their large-scale hydrologic impacts- Water Resour. Res. (1999)

[43] Walling, D. E. (2006), Human impact on land-ocean sediment transfer by the world's rivers, Geomorphology, 79, 192–216.]

[44] https://sandrp.in/2014/07/04/how-do-dams-affect-a-river

[45] Earthjustice (2023). U.S. Sets a Path to Breach the Four Lower Snake River Dams. https://earthjustice.org/press/2023/us-government-sets-a-path-to-breach-the-four-lower-snake-river-dams

[46] Jalali, L., Zarei, M., & Gutiérrez, F. (2019). Salinization of reservoirs in regions with exposed evaporites. The unique case of Upper Gotvand Dam, Iran. Water Research, 157, 587-599. https://www.sciencedirect.com/science/article/abs/pii/S0043135419303197

[47] Soued, C., Harrison, J. A., Mercier-Blais, S., & Prairie, Y. T. (2022). Reservoir CO2 and CH4 emissions and their climate impact over the period 1900–2060. Nature Geoscience, 15(9), 700-705. https://www.nature.com/articles/s41561-022-01004-2.

[48] Rahman, L.M. (2000). The Sundarbans: A unique wilderness of the world. USDA Forest Service Proceedings RMRS-P-15-(2), 143–148.

[49] https://www.internationalrivers.org/resources/reports-and-publications/list-of-dam-threatened-world-heritage-sites/#:~:text=BANGLADESH,
[50] Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B. and Kent, J. 2000, Biodiversity hotspots for conservation priorities, Nature, 403, pp. 853-858.
[51] Choudhury, A. 2013. The mammals of North East India (1st ed.). Guwahati: Gibbon Books, Guwahati, India.
[52] Ahmed, M.F., Das A. and Dutta. S.K. 2009. Amphibians and Reptiles of North east India – A photographic guide. Aaranyak, Guwahati, India. Pp. 73–75.
[53] Choudhury, A. 2018. Natural history of North East India series: Mammals (Vol. 1). Guwahati: Rashmi Prakashan, Guwahati, India.
[54] Williams, C., Tiwari, S.K., Goswami, V, R, de Silva, S., Kumar, A., Baskaran, N., Yoganand, K.S. and Menon,V. 2020. Elephas maximus. The IUCN Red List of Threatened Species 2020
[55] Baruah, D., Hazarika, L. P., Bakalial, B., Borah, D., Dutta, R. and Biswas, S.P. 2012. A grave danger for the Ganges dolphin (Platanista gangetica Roxburgh) in the Subansiri River due to a large hydroelectric project. Environmentalist 32: 85–90.
[56] Wakid, A., Das, P. and Talukdar, B. 2010. Impact of large dams of Arunachal Pradesh and Meghalaya on the endangered Ganges River Dolphin (Platanista gangetica gangetica) of Brahmaputra river system with special references to the Lower Siang, Dibang, Lower Demwe, Lower Subansiri and Kulsi Dam. Report submitted to the Ministry of Environment & Forest, Govt of India, in the public consultation meeting on downstream impact of dams of Arunachal Pradesh in Assam, dated 10th September 2010, Guwahati. Pp. 10.
[57] Sinha, R.K. and Kannan, K. 2014. Ganges River Dolphin: An Overview of Biology, Ecology, and Conservation Status in India. AMBIO 43(8): 1029-1046.
[58] Vagholikar, N. and Das, P.J. 2010. Damming Northeast India. Kalpavriksh, Aaranyak and ActionAid India. Retrieved on February 11, 2020, from https://chimalaya.files.wordpress.com/2010/12/damming-northeast-india-final.pdf.
[59] Choudhury, A. 2018. Natural history of North East India series: Mammals (Vol. 1). Guwahati: Rashmi Prakashan, Guwahati, India.
[60] Grimmett, R., Inskipp, C. and Inskipp, T. 2011. Birds of the Indian Subcontinent. Christopher Helm and Bloomsbury Publishing India Pvt. Ltd., New Delhi, India.
[61] Yadav, P., Kumar, A., Hussain, S. A., & Gupta, S. K. (2020). Evaluation of the effect of longitudinal connectivity in population genetic structure of endangered golden mahseer, Tor putitora (Cyprinidae), in Himalayan rivers: Implications for its conservation. PloS one, 15(6), e0234377.
[62] https://india.mongabay.com/2020/10/how-dams-affect-the-gene-flow-of-golden-mahseer-in-the-himalayas/
[63] https://www.indiawaterportal.org/sites/indiawaterportal.org/files/assessment_of_cumulative_impacts_hydroelectric_projects_aquatic_terrestrial_biodiversity_alaknanda_bhagirathi_uttarakhand_wii_2012.pdf
[64] G Jain V and Tandon S K 2010 Conceptual assessment of (dis)connectivity and its application to the Ganga River dispersal system; Geomorphology 118 349–358.
[65] Yang X, Lu X, Ran L and Tarolli P 2019 Geomorphometric assessment of the impacts of dam construction on river disconnectivity and Cow regulation in the yangtze Basin; Sustainability 11(12) 3427.
[66] Singh M, Tandon S K and Sinha R 2017 Assessment of connectivity in a water-stressed wetland (Kaabar Tal) of Kosi-Gandak interfan, north Bihar Plains, India; Earth Surf. Process. Landf. 42 1982–1996.
[67] Wasson R J, Sundriyal Y P, Chaudhary S, Jaiswal M K, Morthekai P, Sati S P and Juyal N 2013b A 1000-year history of large Coods in the Upper Ganga catchment, central Himalaya, India; Quat. Sci. Rev. 77 156–166.
[68] Veh G, Korup O, von Specht S, Roessner S and Walz A 2019 Unchanged frequency of moraine-dammed glacial lake outburst Coods in the Himalaya; Nat. Clim. Change 9 379–383
[69] Panda S, Kumar A, Das S, Devrani R, Rai S, Prakash K and Srivastava P 2020 Chronology and sediment provenance of extreme Coods of Siang River (Tsangpo–Brahmaputra River valley), northeast Himalaya; Earth Surf. Process. Landf. 45 2495–2511.
[70] Sharma C P, Chahal P, Kumar A, Singhal S, Sundriyal Y P, Ziegler A D, Agnihotri R, Wasson R J, Shukla U K and Srivastava P 2021 Late Pleistocene–Holocene Cood history, Cood-sediment provenance and human imprints from the upper Indus River catchment, Ladakh Himalaya; GSA Bull. 134(1–2) 275–292.
[71] Wasson R J, Chauhan M S, Sharma C, Jaiswal M, Singhvi A K and Srivastava P 2013a Erosion of river terraces as a component of large catchment sediment budgets: A pilot study from the Gangetic Plain; J. Asian Earth Sci. 67–68 18–25.
[72] Wasson R J, Sundriyal Y P, Chaudhary S, Jaiswal M K, Morthekai P, Sati S P and Juyal N 2013b A 1000-year history of large Coods in the Upper Ganga catchment, central Himalaya, India; Quat. Sci. Rev. 77 156–166.
[73] Sundriyal Y P, Shukla A D, Rana N, Jayangondaperumal R, Srivastava P, Chamyal L S, Sati S P and Juyal N 2015 Terrain response to the extreme rainfall event of June 2013: Evidence from the Alaknanda and Mandakini River Val leys, Garhwal Himalaya India; Episodes 38(3) 179–188.
[74] https://www.downtoearth.org.in/urbanisation/how-have-dams-increased-disasters-in-the-himalayas--88632
[75] F. Magilligan et al. The impact of run-of-river dams on sediment longitudinal connectivity and downstream channel equilibrium Geomorphology (2021)
[76] R. Sinha et al. Basin-scale hydrology and sediment dynamics of the Kosi river in the Himalayan foreland J. Hydrol. (2019)
[77] A. Das et al. Nutrient dynamics of Brahmaputra (Tropical River) during monsoon period Desalin. Water Treatm. (2017)
[78] K. Ghosh, Influence of the Anthropogenic and Climatic Factors on the Changing Streamflow, Sediment and Planform Pattern of the Tista River in

the Foothill Alluvial Plain of Eastern Himalaya Doctoral research thesis (2022)

[79] P. Denholm *et al.*Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems, Energy Convers Manag(2004)

[80] Varun *et al.*Life cycle greenhouse gas emissions estimation for small hydropower schemes in India, Energy (2012)

[81] S. Zhang *et al.*Carbon footprint analysis of two different types of hydropower schemes: comparing earth-rockfill dams and concrete gravity dams using hybrid life cycle assessment, J Clean Prod (2015)

[82] https://www.energy.gov/eere/water/tracking-carbon-footprint-hydropower#:~:

[83] Steinhurst W, Knight P, Schultz M. Hydropower greenhouse gas emissions, Cambridge, Massachusetts, USA: 2012.

[84] Fearnside PM. Emissions from tropical hydropower and the IPCC. Environmental Science & Policy. 2015;50:225-39.

[85] Dos Santos, Marco & Rosa, Luiz. (2011). Greenhouse gas emissions from hydropower reservoirs: A synthesis of knowledge. International Journal on Hydropower and Dams. 18. 1-4.

[86] https://www.whoi.edu/press-room/news-release/river-carbon/

[87] Hussain, Manirul (2008): *Interrogating Development: State, Displacement and Popular Resistance in Northeast India*, Sage Publications, New Delhi.

[88] Kaushik Deka, “Dams: The Larger Picture "in Mrinal Talukdar and Kishor Kumar Kalita (eds), Bihat Bandh Aru Axom, Bhabani Print and Publications, Guwahati, 2010.

[89] Linda Chhakchhuak, 2006‘Arunachal Pradesh: Development or Destruction’ in Survey of the Environment 2006.

[90] Arora, V. and Kipgen, N. 2012. ‘We can live without power, but we can’t live without our land’: Indigenous Hmar oppose the Tipaimukh dam in Manipur. Sociological Bulletin 61(1): 109-128.

[91] https://www.internationalrivers.org/news/how-hydropower-development-devastated-the-loktak-wetlands-and-the-livelihoods-of-women-and-communities/

[92] Rawat GS, Adhikari BS. Ecological Studies of High-Altitude Wetlands in the Indian Himalaya. *Journal of the Indian Society of Remote Sensing*. 2018;46(8):139-149.

[93] Saxena R, Gupta S. Socio-Economic Consequences of Large Dam Projects in India: A Study of the Srinagar Hydro Electric Project. *Indian Journal of Economic Development*. 2017;13(2):203-210.

[94] Pant R, Agarwal M, Juyal N. Displacement and Livelihood Changes in the Alaknanda Basin: Post-Dam Construction Scenarios. *Development Practice*. 2019;29(3):329-339.

[95] Bisht M, Joshi RK. Resettlement and Rehabilitation Issues in Large Dams: Lessons from the Srinagar Hydro Electric Project. *Int J Rural Dev*. 2020;39(2):101-110.

[96] Singh S, Rawat R. Tourism Development in the Alaknanda Basin Post-Dam Construction: Opportunities and Challenges. *Tourism Management*. 2021; 83:104234.

[97] Choudhury, N.B. and Dey Choudhury, S.R. 2020a. Potentials and Prospects of Northeast India, with special reference to hydropower. *In:* Aparna Ghosh Das & K. Joy Kumar Singh (Eds.) *Security and Development in South East Asia: Implications for Northeast India.* Scholar Publications, Karimganj, Assam, India. Pp. 215-231. ISBN: 9788194411352.

[98] Moran, E.F., Lopez, M.C., Moore, N., Müller, N. and Hyndman, D.W. 2018. Sustainable hydropower in the 21st century. *PNAS* **115**(47): 11891–11898.

[99] Kohli, Kanchi. (2003). Large Dams in the Northeast India: A Bright Future? Ecologist Asia. 11. 3.

[100] WCD, November 2000, *Dams and Development*: *A New framework for Decision Making*, Earthscan Publications, VA.

[101] Tortajada, C., Altinbilek, D. and Biswas, A.K. 2012. Impacts of Large Dams: A Global Assessment. *In*: Asit K. Biswas and Cecilia Tortajada (*Eds.*) *Water Resources*

[102] Moran, E.F., Lopez, M.C., Moore, N., Müller, N. and Hyndman, D.W. 2018. Sustainable hydropower in the 21st century. *PNAS* **115**(47): 11891–11898.

[103] Bunn, S.E. and Arthington, A.H. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environ Manage* **30**(4): 492-507.

[104] Petts, G.E. and Gurnell, A.M. 2005. Dams and geomorphology: research progress and future directions. *Geomorphology* **71**: 27-47.

[105] Scudder, T. 2012. Resettlement Outcomes of Large Dams. *In*: C. Tortajada *et al.* (*eds.*), *Impacts of Large Dams: A Global Assessment, Water Resources Development and Management,* Springer- Verlag, Berlin, Heidelberg.

[106] *https://www.downtoearth.org.in/urbanisation/himalayan-plunder-how-hydropower-projects-in-the-hills-have-increased-disasters-there-87660#:~:t.*

[107] Misra, A.K. 2014. Climate change and challenges of water and food security. *International Journal of Sustainable Built Environment* **3**(1): 153-165.

[108] Ostad-Ali-Askar, K., Su, R. and Liu, L. 2018. Water Resources and Climate Change. *Journal of Water and Climate Change* **9**(2): 239.

[109] Javadinejad, S., Eslamian, S. and Ostad-Ali-Askari,K. 2021. The analysis of the most important climatic parameters affecting performance of crop variability in a changing climate. *International Journal of Hydrology Science and Technology* **11**(1): 1-25.

[110] Talebmorad, H., Abedi-Koupai, J., Eslamian, S., Mousavi, S.F., Akhavan, S, Ostad-Ali- Askari, K. and Singh, V.P. 2021. Evaluation of the impact of climate change on reference crop evapotranspiration in Hamedan-Bahar plain. *International Journal of Hydrology Science and Technology* **11**(3): 333-347.