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Impact of Srinagar Dam on Wetland Ecosystems and Socio-Economic Dynamics in the Alaknanda Basin, Uttarakhand

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Abstract

Wetlands are critical ecosystems that bridge terrestrial and aquatic environments, playing a vital role in maintaining biodiversity, supporting agriculture, and mitigating natural disasters. This study focuses on the Srinagar Dam in the Alaknanda River basin in the Pauri Garhwal district of Uttarakhand, India. The construction of the Srinagar Hydroelectric Project (SHEP) has transformed the local wetland ecosystem, with significant implications for the environment, society, and economy. The research examines the hydrological regime, assesses the environmental impacts, and explores sustainable management practices for the wetland. Through a micro-level assessment of the wetland's hydrological dynamics, the study highlights the dual role of the dam in providing energy and water resources while posing challenges to local biodiversity and social structures. The findings underscore the need for a balanced approach to wetland management that incorporates ecological conservation and addresses the local population's concerns. The study concludes with recommendations for policy interventions to secure the long-term sustainability of the wetland and its associated ecosystems while enhancing the region's socio-economic benefits.

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Introduction

Wetlands, characterized by their unique ecological features, represent an essential interface between terrestrial and aquatic ecosystems. They play a pivotal role in maintaining biodiversity, regulating water regimes, and providing livelihoods to surrounding communities. The interplay of these factors makes wetlands indispensable to both environmental stability and socio-economic development. Globally, wetlands are recognized for their critical ecosystem services, including water purification, flood control, and carbon sequestration.[1] In the Indian context, wetlands have gained significant attention due to their ecological, economic, and cultural importance and the increasing pressures from development projects such as dams and reservoirs.[2] Wetlands

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are areas where land is saturated with water, either seasonally or permanently, playing a vital role in maintaining biodiversity, filtering water and regulating floods. While the reservoir formed by the Srinagar Dam exhibits some features similar to wetlands, the study area is not a natural wetland but an artificial ecosystem created due to the dam's construction.

The Alaknanda River, one of the primary tributaries of the Ganges, traverses the rugged terrain of Uttarakhand, a state in northern India known for its rich hydrological and ecological resources. The region's topography, dominated by steep slopes and fragile environments, makes it both a source of hydroelectric power and a zone of ecological sensitivity.[3] The construction of the Srinagar Dam, a medium-scale hydroelectric project on the Alaknanda River, has been central to Uttarakhand's strategy for harnessing its hydroelectric potential. However, this development has had significant environmental and socio-economic consequences.[4] The Srinagar Dam, with a capacity of 330 MW, spans from Kaliyasaur to Srinagar, covering a 16-kilometer stretch of the Alaknanda River. Initiated in 2008 and completed by 2014, the dam has submerged vast tracts of agricultural land, forests, and human settlements, affecting both the natural landscape and the livelihoods of local communities.[5] 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 ser-vices in the region (Draft 12th Five Year Plan, 2012-2017).

Wetlands in the Garhwal Himalaya, including those influenced by the Srinagar Dam, are of particular ecological significance. These wetlands, often formed by glacial and fluvial processes, provide critical habitats for flora and fauna.[6] The dam's construction has altered these wetlands' hydrological regimes, affecting their ecological balance and leading to changes in vegetation, water quality, and sedimentation patterns.[7] The river's transformation into a reservoir has created a new wetland ecosystem with distinct characteristics, which now plays a crucial role in the local environment.[8] 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.[9] 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.[10]

In an international context, the challenges the Srinagar Dam poses are mirrored in many parts of the world where large-scale hydropower projects intersect with delicate ecosystems. Countries like China, Brazil, and the United States have faced similar dilemmas in balancing energy production with environmental conservation. For example, the Three Gorges Dam in China has been a subject of global debate, reflecting concerns over ecological degradation, sedimentation issues, and the displacement of millions of people.[11] Similarly, Brazil's Belo Monte Dam in the Amazon Basin has sparked international outcry due to its impact on indigenous communities and the region's biodiversity.[12] These cases highlight the global relevance of sustainable dam management practices, particularly in regions where the ecological consequences can have far-reaching impacts. The international experience underscores the importance of integrating environmental considerations into the planning and implementation of hydropower projects to ensure that the benefits of development do not come at an unsustainable cost to ecosystems and local communities.[13] The development of hydroelectric power in Uttarakhand, while essential for the state's economic growth, has raised critical questions about the sustainability of such projects in ecologically sensitive areas. With its high seismic risk and landslide vulnerability, the Alaknanda Basin presents a challenging environment for large-scale infrastructure projects.[14] The construction of the Srinagar Dam has exacerbated these risks, leading to increased soil erosion, siltation of riverbeds, and changes in river courses, which have further impacted local ecosystems and human settlements.[7]

Furthermore, the dam's impact on downstream hydrology and ecology must be considered. The altered flow regimes have affected aquatic habitats, reduced water availability for downstream communities, and led to the drying up of water sources in certain areas.[15] The changes in river

dynamics have also affected fish populations and other aquatic life, disrupting traditional fishing practices and contributing to the decline of local biodiversity.[3] In the context of these multifaceted impacts, this study seeks to explore the ecological and socio-economic consequences of the Srinagar Dam on the wetland ecosystems and communities of the Alaknanda Basin. The research aims to assess the changes in hydrological regimes, vegetation patterns, biodiversity within the newly formed wetland, and the socio-economic challenges faced by displaced and affected communities. By conducting a micro-level assessment, the study will provide insights into the sustainability of such large-scale infrastructure projects in ecologically fragile regions and offer recommendations for better management and conservation practices.

The importance of this research lies in its potential to inform policy and decision-making processes regarding the development of hydroelectric power in Uttarakhand and similar regions. As the state continues to harness its hydroelectric potential, it is crucial to balance the need for energy with the imperative of conserving the environment and ensuring the well-being of local communities. The findings of this study contributed to the ongoing discourse on sustainable development in the Himalayas and highlight the need for a more integrated approach to managing the region's natural resources.[13]

Materials and Methods

The research is conducted through a combination of field surveys, remote sensing techniques, and data analysis to understand the ecological and socio-economic changes brought about by dam construction. A base map was generated at a scale of 1:50,000, utilizing LISS IV satellite imagery and high-resolution Google images (1:10,000) to delineate channel features. Google Earth data from 2010 and 2018 were analyzed to detect changes in the channel's morphological characteristics. The decade-spanning, high-resolution, geo-referenced satellite images from Google Earth were found to be within an acceptable error range. The Google images were digitized into KML format and subsequently imported into ArcGIS 10 by converting the KML files into shapefiles. These shapefiles were then used to create a database within ArcGIS, with attributes added as needed, such as polygon areas.

Some pilot or primary study was done by including interviews with tourists and individual interviews with administrative personnel. These approaches were used to gather expert opinions and information, beginning with a broad overview of the area and progressively narrowing down to specific issues related to tourism and the management of the Srinagar dam. Thus, the study on Srinagar dam, the author took information from two villages Kaliysaur and Dhara Devi. Secondary data includes satellite images from two different years, 2010 and 2018, which were downloaded from the USGS website NASA. Landsat 5 TM and Landsat 8 OLI/ TIRS images, both with 30-metre resolution, were downloaded, and unsupervised hybrid classification was run to obtain the specific collection of river water maps for the two years. Digital Elevation Model SRTM-DEM of the study area, which has a 30-metre spatial resolution, was downloaded from NASA's USGS website.

This study aims to thoroughly investigate the geographical aspects of wetlands, focusing on their spatial distribution and physical characteristics. It also conducts a detailed micro-level assessment of the wetland's hydrological regimes, including water flow patterns and seasonal variations. Finally, the study proposes suitable conservation measures to ensure the sustainable management of wetland ecosystems, addressing both ecological and community needs.

Study Area

Uttarakhand, a northern state of India, borders China in the north and Nepal to the east. Covering an area of 53,483 square kilometers, it lies between the latitudinal coordinates of 28° 43' N and 31° 28' N, and longitudinal coordinates of 77° 34' E and 81° 03' E. The geographical diversity of Uttarakhand is reflected in its varied climate, with temperate conditions prevailing in most regions, except the plains, where the climate is sub-temperate. The state receives an average annual rainfall of around 1,550 mm. Temperatures vary significantly, dropping below freezing in the higher altitudes and reaching up to 43°C in the lower plains.[30]

This study focuses on the submergence zone of the Srinagar dam, a medium-scale project located on the Alaknanda River near Srinagar town in the Pauri Garhwal district of Uttarakhand. The research aims

to conduct an in-depth geographical analysis of the wetland areas impacted by the project, assess the micro-level hydrological regimes, and propose suitable conservation measures to mitigate the adverse effects on the ecosystem.

The submergence area associated with the Srinagar dam extends from an elevation of approximately 500 meters above sea level (asl) at the dam site near Koteshwar, rising to about 600 meters near the village of Narkota. Pauri Garhwal, located centrally within the Garhwal Himalayas, lies between latitudes 29° 20' N and 30° 15' N and longitudes 78° 10' E and 79° 20' E. The district covers an area of 5,329 square kilometres, with 61.72% (3,289 square kilometres) of its total geographical area under forest cover.

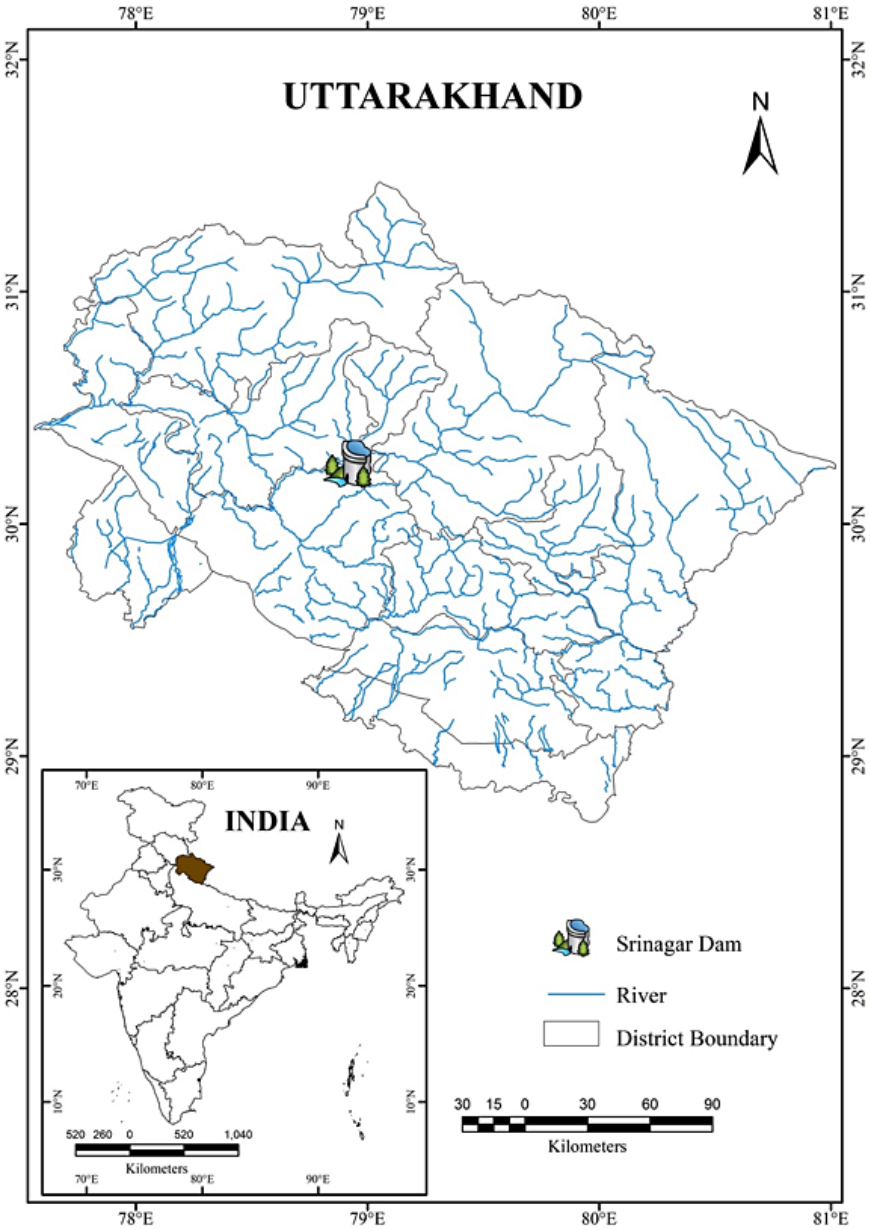


Fig.1: Map of Study area

Results and Discussion

The Srinagar Dam is strategically positioned near Koteshwar, in proximity to the North Almora Thrust, and is situated about 6 kilometres upstream of Srinagar town on the right bank of the Alaknanda River.[16] The construction of the Srinagar Dam has affected a total of 24 villages. In the Tehri Garhwal district, there are 15 villages, including Dhari, Barkot, Ghorsali, Margaon, Gandasu, Madhi, Naithana, Mangsu, Gugli, Maindu, Nagyana, Naur, Sankron, Supana, and Thapli. Additionally, nine villages are situated in the Pauri Garhwal district: Dungripanth, Kotchula, Koteshwar, Kaliasaur, Panthlagga, Pharasu, Sem, Shiraurbagar and Swit. The total area impacted by the dam's construction is around 1,900 hectares, of which 475 hectares have been acquired for various project-related infrastructures. The affected land includes 33% of agricultural land, 46% of culturable wasteland, 3% of forest land and 18% of land is others.

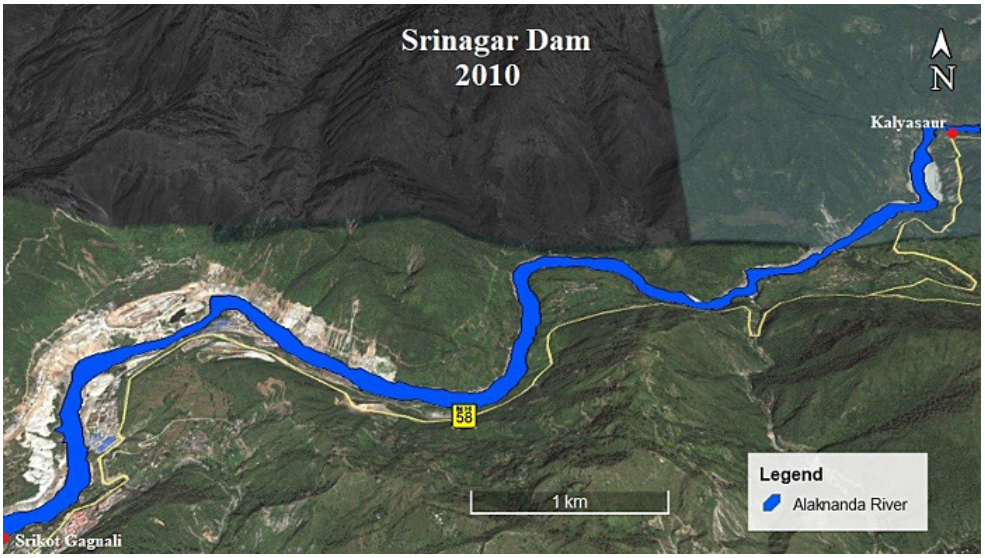
The project has resulted in the loss of approximately 66 hectares of reserve forest and 273 hectares of Civil Soyam forest land due to submergence and land acquisition for other project facilities. In total, 339 hectares of forest area have been impacted by the project. The reservoir created by the dam will submerge the historically significant Dhari Devi temple in Kaliasaur village. Approximately 2 kilometers of the Rishikesh-Badrinath National Highway (NH 7) are expected to be submerged. The project includes the construction of a 73-meter-high barrage designed to provide a 69-meter water head for power generation. The amount of deforestation because of costruction of the Srinagar Dam has stricken the inner forest biodiversity of the region with up to a total of 339 hectares of forest land alleged loss thereof. The report, while examining the effects on the wetland species, has not properly dealt with the effects of forest vegetations and fauna. Mammals, birds, pollinators and other organisms thrive in the diverse forests where they enjoy the services of the forests; those services range from carbon capture and water retention to provision of numerous other services. It is most likely that the loss of forests due to submergence and land clearing has caused a change in the habitat structure that has led to the extinction of the majority of the species living in the forests. Also, the disturbance of such ecosystems can lead to disturbances in species interactions, food webs and distort the balance of nature in the area.

Although the reservoir has been described as having a natural wetland ecosystem, an explanation in the light of the processes leading to this change is imperative. Wetlands are formed from dynamic or complicated flow patterns to a constant level of water, where the change in local hydrology has led to favourable circumstances for wetland creation. The water level adjustment and gradual reduction of current forces towards the enclosed body created zones of sediment deposition along the water body's edges hence, shallow water zones, which is a characteristic of wetlands. These are the features that cause the wetland conditions to set in with respect to the reservoir. Equally, the biotic components in the region may have changed considerably. With the changes in moisture regimes, it is possible that besides hydrophytic plants, amphibians, some birds, and invertebrates adapted to wetland regimes may have been introduced. The appearance of such species is a signal towards an environment development in the direction of that of a natural wetland. But it should also be understood that such a development is not equal to that of the complexity found in the original wetlands. The reservoir is still an artificial one, thus its habitats may not be as diverse or as hardy as the true saline and freshwater ecosystems.

In addition, the possible contribution of environmental efforts, such as tree planting, creation of buffer zones or the planting of indigenous wetland plants, should be investigated to determine if they played a role in the improvement of the wetland. In the absence of specific measures, the ecological transformation may remain only partially realized, with the reservoir containing a limited range of functional characteristics typically found in natural wetlands. To comprehend the processes leading to existed and maintenance of this new categorising more in depth studies and monitoring of long-term hydrological regimes, sediment regimes and species compositions are required. Such actions would offer fundamental knowledge regarding the transformational processes taking place and assist in determining if this artificial wetland would over the years be able to perform similar ecological functions as natural wetlands do.

Geographical and Hydrological Impact

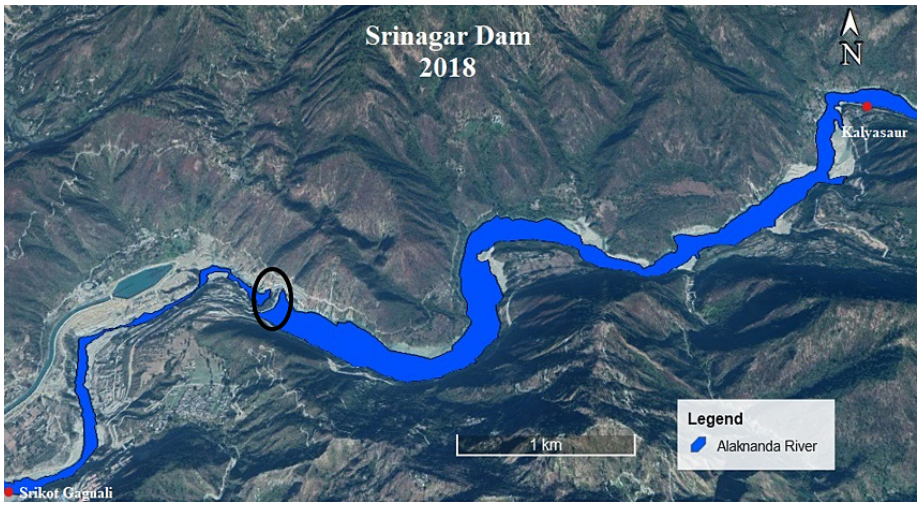
The construction of the Srinagar Dam has significantly altered the geographical and hydrological characteristics of the Alaknanda Basin. The remote sensing analysis reveals substantial changes in land use and land cover over the past decade. The pre-dam landscape, characterized by a mix of forested areas, agricultural lands, and natural wetlands, has transformed, with a notable reduction in forest cover and an increase in water bodies due to the formation of the reservoir. The land cover analysis shows that forested areas decreased by approximately 25%, while the water-covered areas expanded significantly, submerging over 1900 hectares of land.



Source: Google image data October, 2010

Fig. 2: Alaknanda River, before construction of the dam from Srinagar to Kaliyasaur

In Figure 2, the reservoir is at the beginning of construction in 2010. That map clearly defines the area of the reservoir, at that time, the reservoir was small compared to today. This stretch of the Srinagar dam reservoir on the Alaknanda River from Srinagar to Kaliasaur.



Source: Google Image data, October 2018

Fig. 3: Srinagar dam (black circle) after the construction from Srinagar to Kaliyasaur.

In Figure 3, the data collected from Google Maps shows today's reservoir situation. The project involved in constructing a concrete dam that spanned from bank to bank across the Alaknanda River, creating a 16-kilometer-long artificial lake. According to the original design, the dam was built to a height of 60 meters, effectively preventing the submersion of the ancient Dhari Devi temple. The accumulation of silt and sand within the Srinagar Hydroelectric Project (330 MW) reservoir, commonly referred to as the Srinagar dam, could potentially fuel future floods, threatening previously safe homes and farmlands along the river's course.

Hydrologically, the dam has led to altering natural water flow regimes. The reservoir has created a static water body, replacing the dynamic flow of the river. This change has impacted the seasonal flow patterns, reducing water availability downstream during dry seasons and increasing water retention during monsoon periods. The hydrological assessment indicates that these changes have increased sedimentation within the reservoir, affecting water quality and reducing the reservoir's adequate storage capacity over time. The alteration of flow regimes has also impacted the groundwater recharge rates, further complicating the region's water availability.

The construction of the Srinagar Dam on the Alaknanda River has profoundly impacted the weland ecosystems and socio-economic dynamics within the Alaknanda Basin. These impacts encompass ecological disruptions, hydrological alterations, and significant socio-economic consequences for the local communities.

Ecological Impacts

The creation of the Srinagar Dam has led to the formation of a large reservoir, which has substantially altered the natural wetland ecosystems in the region. Before the dam's construction, the wetlands in the Alaknanda Basin supported diverse flora and fauna, contributing to the region's ecological balance. However, the reservoir's formation has submerged critical habitats, leading to a significant loss of biodiversity. Native plant species, particularly hydrophytes that thrived in the dynamic riverine environment, have been replaced by species more suited to the altered hydrological conditions. This change has cascading effects on local fauna, especially species dependent on specific wetland vegetation for habitat and sustenance.[17-19]

Furthermore, the dam has disrupted the river's natural flow, altering sediment transport and deposition patterns. The reduction in sediment downstream has impacted the fertility of agricultural lands and the spawning grounds of fish species, particularly the Mahaseer, a keystone species in the region's aquatic biodiversity. Although the reservoir has created new wetland areas, these artificial ecosystems need more complexity of the original wetlands, raising concerns about their long-term sustainability, especially amidst ongoing environmental changes and anthropogenic activities.[20,21]

Hydrological and Geological Impacts

The hydrological impacts of the Srinagar Dam are extensive. The dam has significantly modified the natural hydrological cycle of the Alaknanda River, leading to changes in water availability, particularly during dry seasons. The regulation of river flow by the dam has reduced the frequency and intensity of natural floods, which, while beneficial in preventing flood damage, has disrupted the natural processes critical for maintaining downstream wetland health. Additionally, the dam has exacerbated soil erosion in areas around the reservoir, where fluctuating water levels have destabilized the banks.[22,23]

From a geological perspective, the Srinagar Dam is in a seismically active region, with several major faults, including the Main Central Thrust and the North Almora Thrust, located nearby. The dam's construction has heightened the region's vulnerability to seismic events and landslides, as evidenced by the catastrophic 2013 Uttarakhand floods. The dam's presence has also contributed to changes in the river's course during heavy rainfall, increasing flood risks for downstream communities.[24,25]

The historical data would help in demonstrating the evolution of river flow regimes and its consequences in terms of water availability, recharge of aquifers and enhanced flooding threats in the lower regions. Similarly, ecological parameters such as past biodiversity metrics can be used assess the effects of efficient habitat alteration on loss

of native species and presence of potential invasive non – native species. Likewise, pre-project socio-economic assessments can provide information regarding the changes in local markets and communities, their relocation or change in the scope of farming activities. The comparative studies in other massive dam constructs such as the three gorges dam in China and the Belo Monte dam in Brazil have revealed extensive deterioration of wildlife and displacement of people over time. This illustrates the need to appreciate the past as well as the present findings in order not to just look at the short term impacts but also the long-term implications. Hence, there is an urgent need to perform detailed comparative studies in order to make better management decisions in the future about environmental rehabilitation of the area and about enhancing the adaptive capacity of the local population.

Socio-Economic Impacts

The socio-economic impacts of the Srinagar Dam on local communities in the Alaknanda Basin have been profound. The dam's construction has displaced approximately 24 villages, with vast tracts of agricultural land submerged. This loss has severely impacted the livelihoods of residents, many of whom relied on farming as their primary source of income. Compensation provided to displaced communities has often needed to be improved, leading to economic hardship and social dislocation.[26,27]

The building of the Srinagar Dam led to the submergence of 24 villages thus its effects on the local communities were both economically and socially. Still, the report does not provide extensive statistics on the extent of the displacement and especially such key facts as the number of individuals displaced, the loss of certain areas of land and data concerning compensations and resettlements. Displacement creates severe challenges to the socio-economics of the individuals concerned usually in the form of loss of residence, agricultural and business establishments which in turn may cause poverty and social disintegration for quite some time. In most cases, justice is never done to the displaced people because no compensation, cash or even a piece of land to farm, is reimbursed to them; as a result, the displaced families find it hard to return to anything resembling a normal way of life. With such pathetic designs of resettlement, which do not work, poverty worsens, there is hunger, and people are displaced to the cities in search of jobs. In addition, such a situation creates a separation of people who had been living together with certain characteristics for a long time and this contributes to the erosion of culture and unity.

Furthermore, the dam has disrupted the region's traditional socio-economic fabric. Many displaced individuals have migrated to urban areas in search of employment, eroding traditional community structures and cultural practices. While new economic activities, such as tourism related to the dam and reservoir, have emerged, the benefits have been unevenly distributed, with many communities remaining marginalized. The failure to adequately address the socio-economic needs of affected populations has contributed to ongoing poverty and social instability in the region.[28,29]

Conclusion

The Srinagar Dam has significantly altered the environmental and socio-economic dynamics of the Alaknanda Basin. While the dam has contributed to hydroelectric power generation and creating a new wetland ecosystem, these developments have come at considerable costs. The study reveals that the dam has disrupted natural hydrological regimes, leading to the degradation of native wetlands and loss of biodiversity. Additionally, local communities have faced severe socio-economic challenges, including the loss of agricultural land, displacement, and changes in traditional livelihoods.

These results highlight the importance of adopting sustainable development practices that harmonize economic progress with environmental preservation and social welfare. The study recommends implemting a comprehensive wetland management plan focused on restoring native vegetation and controlling invasive species. Additionally, supporting alternative livelihoods for affected communities, such as eco-tourism, is crucial for enhancing socio-economic resilience.

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Informed Consent Statement
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Author Contributions
- **Ashwani** was responsible for conceptualising and designing the experiments, analysing and interpreting the data as well as preparing and editing the manuscript.
- **Abhay Kumar** conducted the literature review, carried out experimental procedures, performed data analysis and reviewed the results.
- **Anshul Tyagi** played a role in data analysis and in manuscript preparation.

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