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Cumulative Environmental Impacts of the Suki Kinari Hydropower Project (SKHPP) on the Kunhar River Ecosystem: Implications for Sustainable Hydropower Management

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Abstract *— Although hydropower development is widely regarded as an important renewable energy source, large-scale hydropower infrastructure inside delicate river systems may cause long-term ecological instability. This study looks at how the Suki Kinari Hydropower Project (SKHPP) in northern Pakistan has affected the ecosystem of the Kunhar River over time. The study assesses habitat fragmentation, disturbance of sediment movement, hydrological change, and effects on aquatic biodiversity, especially trout populations. Environmental assessment reports, ecological indicators, and published scientific literature were used in a mixed-methods approach. The results show that river morphology and aquatic ecosystems have been adversely impacted by downstream flow reduction and sediment imbalance. In order to lower ecological risks related to future hydropower growth, the study emphasizes the importance of environmental flow control, biodiversity conservation, and sustainable hydropower governance.*

Keywords*— Suki Kinari Hydropower Project (SKHPP), Kunhar River Ecosystem, Cumulative Environmental Impacts, Sustainable Hydropower Management, Renewable Energy Development, Environmental Sustainability, Ecological Integrity, River Basin Management.

I. BACKGROUND

Freshwater accessibility, biodiversity management, tourism, and local livelihoods are all significantly supported by mountain river ecosystems. Rising energy demand in Pakistan's northern mountainous regions, where river systems are inherently sensitive, has sped up the development of hydropower. Despite the fact that hydropower is typically seen as clean energy, poorly managed dams have the potential to seriously harm the environment.

One significant run-of-river hydropower project in Khyber Pakhtunkhwa is the Suki Kinari Hydropower Project (SKHPP), which is situated on the Kunhar River. Environmental issues with flow diversion, altered sediment transport, and habitat fragmentation have surfaced despite its contribution to the country's energy production. When these effects are coupled with other stressors like increased tourism, climate variability, and land-use change, they become more severe.

Because their spawning and migrating patterns depend on stable river conditions, aquatic species like brown trout (Salmo trutta) and snow trout (Schizothorax spp.) are especially vulnerable to hydrological disturbance. The cumulative environmental effects of SKHPP are assessed in this study, along with its implications for sustainable hydropower management.

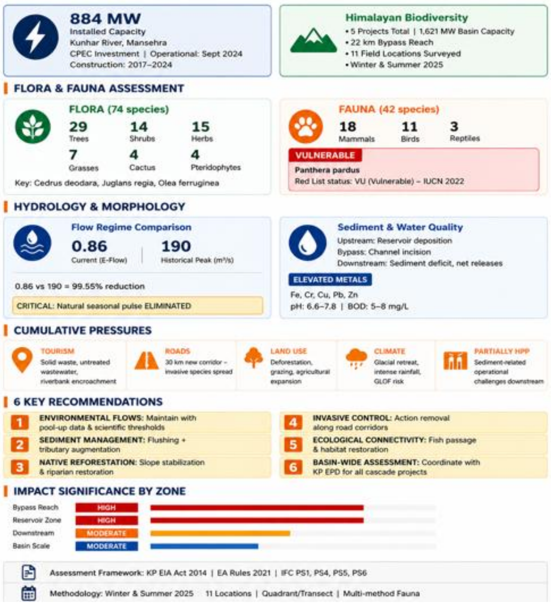

Fig.1: Suki Kinari Hydropower Project

The Suki Kinari Hydropower Project (SKHPP) is an 884 MW renewable energy project located on the Kunhar River in Kaghan Valley, District Mansehra, Khyber Pakhtunkhwa. Developed under the China–Pakistan Economic Corridor (CPEC) with support from China Energy Group Company Limited, the project represents a major investment in Pakistan's transition toward sustainable and locally generated energy. Following its construction between 2017 and 2024, the project commenced commercial operations in September 2024 and has become the largest hydropower facility on the Kunhar River.

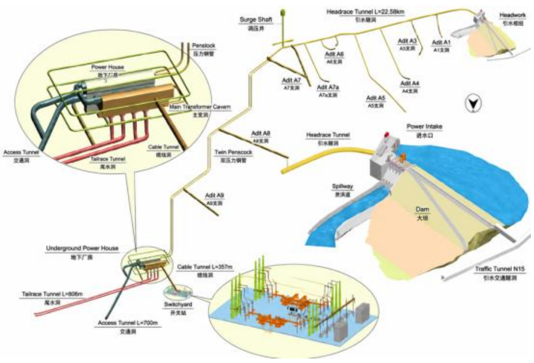

Fig.2: 884 MW Suki Kinari Hydropower Project

The project is situated within the Himalayan biodiversity hotspot, an environmentally sensitive region known for its rich ecological resources and diverse habitats. While the project contributes significantly to national energy security and the reduction of dependence on imported fossil fuels, its location within a fragile mountain ecosystem necessitates careful environmental management and continuous monitoring of ecological conditions.

The Kunhar River basin originates from glacial sources at high elevations and flows through a variety of ecological zones, including moist temperate forests, deodar woodlands, and subtropical vegetation communities. The basin supports numerous plant and animal species, including economically important trees, medicinal plants, cold-water fish species, and wildlife of conservation concern such as the Common Leopard. In addition, the river receives water from several tributaries that maintain the hydrological and ecological connectivity of the watershed.

Given the ecological importance of the region and the scale of hydropower development, a Cumulative Impact Assessment (CIA) was undertaken to evaluate environmental changes associated with project operations. Unlike the original Environmental Impact Assessment (EIA), which focused on predicted impacts before construction, the CIA examines actual post-construction conditions and assesses how project-related effects interact with other regional pressures such as tourism growth, road development, deforestation, grazing activities, agricultural expansion, and climate change.

The assessment was conducted in accordance with the requirements of the Khyber Pakhtunkhwa Environmental Protection Agency (KP EPA), relevant environmental regulations, and international standards, including the International Finance Corporation (IFC) Performance Standards. Field investigations covering ecological, hydrological, and geomorphological aspects were carried out during winter and summer 2025 across multiple locations within the project area. The findings provide a comprehensive understanding of current environmental conditions and support the development of adaptive management measures for the sustainable operation of the project and the protection of the Kunhar River ecosystem.

II. LITERATURE REVIEW

Through biological fragmentation, sediment retention, and flow regulation, hydropower production drastically changes natural river dynamics. Hydrological change affects aquatic biodiversity and lowers habitat quality in mountain river ecosystems, according to FAO (2003). In a similar vein, Grill et al. (2019) stressed that building dams disrupts river connectivity and jeopardizes the ecological stability of freshwater.

Because it assesses the aggregate effects of several environmental stressors rather than individual project-level impacts, cumulative impact assessment, or CIA, has grown in importance as an environmental management strategy. According to Therivel and Ross (2007), when projects are evaluated separately, cumulative ecological deterioration is frequently underestimated.

Fish species found in cold waters are extremely sensitive to changes in their surroundings. Hydropower development may interfere with trout migration routes, spawning circumstances, and juvenile survival rates, according to research by Khan et al. (2020). The aquatic ecological equilibrium in Himalayan river systems is further threatened by habitat degradation and changed flow patterns.

While environmental monitoring reports for SKHPP offer valuable baseline data, few scholarly studies have incorporated these results into a more comprehensive framework for sustainability and management. In order to close that gap, this study looks at both practical environmental management factors and cumulative ecological repercussions.

Hydropower is widely recognized as a renewable and low-carbon energy source that contributes significantly to energy security and economic development. However, large-scale hydropower projects often produce substantial environmental and ecological changes, particularly in mountainous river systems. These changes may include alterations in river flow regimes, sediment transport processes, aquatic habitats, biodiversity distribution, and ecosystem functioning. Consequently, cumulative impact assessments (CIA) have become an essential tool for evaluating the combined effects of hydropower projects and other anthropogenic activities within a watershed.

The Kunhar River Basin, located within the Himalayan biodiversity hotspot, supports a diverse range of ecological communities, including temperate forests, riparian habitats, cold-water fisheries, and wildlife species of conservation importance. Previous environmental studies have identified the basin as an ecologically sensitive area where hydrological integrity directly influences biodiversity conservation and local livelihoods. The river provides habitat for economically and ecologically important species, including Brown Trout and Rainbow Trout, while surrounding forests support species such as Cedrus deodara, Juglans regia, and the Common Leopard (Panthera pardus).

Scientific literature indicates that hydropower dams can significantly modify natural river processes by reducing downstream flows, altering seasonal discharge patterns, and trapping sediments within reservoirs. These changes often result in river channel adjustments, reduced sediment availability downstream, habitat fragmentation, and declining aquatic biodiversity. In cascade hydropower systems, where multiple dams exist along the same river, these impacts may accumulate and intensify over time. Studies of mountain rivers have demonstrated that cumulative effects are often more significant than the impacts of individual projects because multiple developments interact with existing environmental pressures.

The concept of cumulative impacts extends beyond hydropower infrastructure alone. Research emphasizes that environmental conditions in river basins are influenced by multiple interacting factors, including tourism development, road construction, deforestation, overgrazing, agricultural expansion, and climate change. These activities contribute to vegetation loss, habitat fragmentation, soil erosion, water quality degradation, and increased ecological stress. Therefore, cumulative assessments must consider both project-related impacts and broader regional drivers of environmental change.

Climate change has emerged as an additional concern in Himalayan watersheds. Glacial retreat, changing precipitation patterns, and increased frequency of extreme weather events can alter river discharge and sediment transport dynamics. Research has shown that these changes may increase flood risks, affect aquatic ecosystems, and create uncertainty in long-term hydropower operations. In combination with existing infrastructure development, climate-induced hydrological variability can further influence ecological conditions throughout river basins.

Aquatic biodiversity is particularly vulnerable to hydropower development. Altered flow regimes, hydropeaking, thermal changes, and migration barriers can affect fish reproduction, spawning success, and habitat connectivity. Trout populations are often used as indicators of river ecosystem health because of their sensitivity to environmental disturbances. Previous studies in the Kunhar River have documented the ecological importance of trout fisheries and highlighted the need for environmental flow management and fish conservation measures to sustain aquatic biodiversity.

Water quality studies conducted in Himalayan rivers generally indicate that these systems maintain good ecological conditions despite increasing development pressures. However, sediment accumulation and changes in sediment chemistry may affect benthic organisms and aquatic vegetation. Research suggests that continuous monitoring of water quality, sediment characteristics, and ecological indicators is necessary to identify emerging cumulative impacts and support adaptive management. The Kunhar River currently exhibits favorable water quality conditions for sensitive aquatic species, although sediment management remains an important environmental consideration.

International best practices, including the International Finance Corporation (IFC) Performance Standards and cumulative impact assessment guidelines, emphasize the importance of basin-level environmental planning and coordinated management among multiple project developers. Such approaches promote integrated monitoring of river hydrology, biodiversity, sediment transport, and ecosystem services while ensuring that mitigation measures are implemented consistently across projects. Recent assessments recommend coordinated cumulative impact studies for all existing and proposed hydropower developments in the Kunhar River Basin to support sustainable resource management and biodiversity conservation.

Overall, existing literature demonstrates that hydropower development can provide substantial socioeconomic and energy benefits but may also generate cumulative environmental impacts when combined with other regional stressors. Effective environmental flow management, sediment control, habitat restoration, biodiversity conservation programs, and long-term monitoring are widely recognized as critical measures for maintaining ecological integrity in mountain river systems. These findings provide the theoretical foundation for assessing the cumulative environmental impacts of the Suki Kinari Hydropower Project within the broader context of the Kunhar River Basin.

Research Objectives

1. To investigate the cumulative ecological impacts of hydropower development in the Kunhar River Basin.
2. To compare upstream and downstream environmental conditions affected by hydropower operations.
3. To assess the impacts of altered flow regimes and sediment dynamics on trout habitat suitability and population sustainability.
4. To evaluate trout lifecycle vulnerability using ecological indicators associated with hydropower development.

Research Questions

1. How has hydropower development altered ecological conditions within the Kunhar River Basin?
2. What differences exist between upstream and downstream river segments in terms of flow, sediment transport, and habitat quality?
3. How do hydropower-induced environmental changes affect trout populations across different life stages?
4. Which cumulative environmental impacts pose the greatest threat to aquatic ecosystem sustainability in the study area?

III. RESEARCH METHODOLOGY

This study employed a mixed-methods approach, integrating quantitative ecological data with qualitative environmental assessment. Secondary data were collected from hydrological records, biodiversity surveys, cumulative impact assessment (CIA) reports, and peer-reviewed literature on hydropower-related environmental impacts.

The analysis focused on a comparative assessment of upstream and downstream river segments affected by hydropower operations. Key indicators included river flow variability, sediment transport dynamics, aquatic habitat quality, and trout population vulnerability across different life stages.

Environmental impacts were evaluated using descriptive and comparative ecological analyses, supported by thematic review of institutional reports and published studies. Ecological indicators from the Trout Lifecycle Environmental Impact Matrix were used to assess hydropower-related effects on spawning, egg, fry, juvenile, and adult trout stages. The integration of ecological evidence and institutional observations enabled an assessment of the relationship between hydropower development and cumulative degradation of river ecosystems.

IV. DATA ANALYSIS

The analysis indicates that hydropower development has significantly altered the hydrological and ecological dynamics of the Kunhar River. Comparative assessment of upstream and downstream river reaches revealed noticeable changes in flow regimes, sediment transport processes, habitat quality, and trout population sustainability.

The Cumulative Impact Assessment (CIA) identifies flow alteration, sediment trapping, ecological fragmentation, and trout lifecycle impacts as major environmental concerns associated with hydropower operations in the basin.

- *Hydrological Alteration and Environmental Flow Reduction*

The findings show that dam operation and water diversion have modified the river's natural flow regime, particularly within bypassed and downstream sections. Reduced environmental flows during low-flow seasons have decreased water depth, wetted channel area, and habitat availability for aquatic organisms.

Evidence from the CIA report, including observations of dry riverbeds along diversion reaches and downstream of the dam, indicates that flow reduction has disrupted ecological connectivity and diminished the river's capacity to sustain aquatic biodiversity. The establishment of environmental flow regimes was identified as a critical requirement for maintaining ecosystem health and sustainable river management.

- *Sediment Transport Disruption and River Morphology Changes*

Hydrological analysis further revealed substantial disruption of sediment transport processes. Reservoir impoundment and flow regulation have reduced downstream sediment delivery, leading to sediment starvation and geomorphological changes within the river channel. The CIA specifically highlights downstream erosion resulting from sediment deprivation and identifies sediment change as a key factor affecting river morphology and ecological conditions. Reduced sediment availability contributes to riverbed armoring, loss of spawning gravels, and degradation of benthic habitats essential for aquatic species. These changes have altered natural channel processes and reduced habitat complexity downstream of the project area.

- *Impacts on Trout Populations and Aquatic Biodiversity*

Trout populations emerged as one of the most vulnerable ecological receptors. The CIA identifies migration barriers, hydropeaking effects, thermal stress, and habitat fragmentation as significant pressures affecting trout lifecycle stages. These impacts reduce recruitment success, disturb spawning activities, and contribute to population fragmentation. The degradation of spawning grounds caused by sediment deficits and altered flow conditions particularly threatens egg incubation and juvenile development. Although hatchery-based fish stocking programs have contributed to partial population recovery, the assessment notes potential ecological risks, including genetic dilution and reduced resilience of wild trout populations.

- *Habitat Fragmentation and Ecological Stress*

Ecological stress was found to be most pronounced within bypassed river sections where reduced flows and physical barriers have fragmented aquatic habitats. Fragmentation limits species movement, weakens biological connectivity, and reduces the availability of suitable habitats for fish and macroinvertebrates. The CIA identifies hydropower cascade effects as a cumulative pressure that causes flow alteration, sediment trapping, and ecological fragmentation throughout the river basin. Consequently, biodiversity conditions in affected reaches are less stable and more vulnerable to additional environmental disturbances.

- *Cumulative Environmental Pressures*

The analysis demonstrates that hydropower impacts do not occur in isolation but interact with multiple environmental stressors already affecting the Kunhar River basin. Tourism development, road construction, informal settlements, overgrazing, deforestation, agricultural expansion, and climate change collectively intensify ecological degradation. Tourism-related infrastructure and increasing visitor numbers contribute to waste generation, sewage discharge, riverbank encroachment, and aquatic disturbance, while road construction and settlements promote vegetation clearance, soil erosion, and habitat degradation. Overgrazing and deforestation further accelerate habitat fragmentation and biodiversity decline.

Climate change represents an additional source of ecological vulnerability. The CIA identifies glacial retreat, altered precipitation patterns, sediment shifts, flash floods, and increased hydrological variability as emerging threats to river ecosystems. These climate-induced pressures compound hydropower-related impacts by increasing environmental uncertainty and reducing the adaptive capacity of aquatic habitats and trout populations.

Overall, the data indicate that hydropower development has contributed to cumulative ecological degradation within the Kunhar River system through alterations in flow regimes, disruption of sediment transport, habitat fragmentation, and increased pressure on trout populations. These impacts are amplified by concurrent environmental stressors, including tourism expansion, land-use change, and climate variability. The findings suggest that maintaining adequate environmental flows, restoring sediment continuity, protecting critical trout habitats, and implementing basin-wide cumulative impact management strategies are essential for preserving the ecological integrity of the Kunhar River.

V. DISCUSSION

The findings indicate that the cumulative environmental impacts of the Suki Kinari Hydropower Project (SKHPP) extend beyond individual project-level disturbances and contribute to broader ecological pressures within the Kunhar River basin. The interaction of hydropower operations with existing environmental stressors, including climate variability, tourism development, and land-use change, has increased the vulnerability of river ecosystems and reduced their ecological resilience.

Hydrological alteration remains one of the most critical environmental concerns. Reduced environmental flows in downstream and bypassed river reaches have affected aquatic habitat availability, ecological connectivity, and biodiversity. These findings are consistent with studies from other Himalayan river systems, where flow regulation has disrupted fish migration, spawning behavior, and overall ecosystem functioning.

Sediment transport disruption represents another significant long-term challenge. The reduction of sediment delivery downstream has altered river morphology, contributed to riverbed armoring, and degraded spawning habitats for trout and other aquatic species. Since natural sediment dynamics are essential for maintaining habitat quality and ecological productivity, continued sediment imbalance may further reduce the suitability of cold-water river ecosystems.

Fig.3: Cumulative Impact Assessment Report 2025 – CPEC Secretariat

The results also highlight the importance of considering cumulative impacts rather than assessing hydropower projects in isolation. Multiple environmental pressures acting simultaneously can amplify ecological degradation and weaken the adaptive capacity of river ecosystems.

From a management perspective, sustainable hydropower development requires stronger environmental monitoring, adaptive environmental flow management, sediment management measures, and basin-wide cumulative impact assessment frameworks. Integrating ecological sustainability into hydropower planning and operational decision-making is essential to balance energy generation objectives with the long-term conservation of the Kunhar River ecosystem.

VI. CONCLUSIONS

This study demonstrates that the environmental impacts of the Suki Kinari Hydropower Project (SKHPP) extend beyond localized project disturbances and contribute to cumulative ecological pressures within the Kunhar River ecosystem. Alterations in river flow, disruption of sediment transport, and habitat fragmentation have collectively affected aquatic biodiversity, ecological connectivity, and the long-term stability of riverine habitats. These impacts are further intensified by other environmental stressors operating within the basin, highlighting the importance of evaluating hydropower development from a cumulative impact perspective.

The findings emphasize that achieving sustainable hydropower development requires balancing renewable energy generation with the protection of ecological integrity. Effective environmental flow implementation, sediment management, biodiversity conservation measures, and continuous ecological monitoring are essential to minimize adverse impacts. Furthermore, basin-scale planning and cumulative environmental impact assessments should be integrated into future hydropower policies and decision-making processes. Adopting these approaches will help ensure that hydropower development contributes to energy security while safeguarding the ecological health and resilience of the Kunhar River ecosystem.

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