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REVIEW ARTICLE

ECOLOGICAL IMPACTS OF WATERWHEEL DEPLOYMENT ON RIVER ECOSYSTEMS: A MINI REVIEW

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ABSTRACT : Waterwheels are re-emerging as decentralized renewable energy solutions. They offer economical electricity to rural populations and adhere to sustainable development objectives. Nonetheless, their ecological effects on river ecosystems are less examined in comparison to huge dams and traditional hydropower. This brief review consolidates existing research regarding the hydrological, geomorphological, and ecological impacts of waterwheel installations. Hydrological alterations encompass diminished downstream flows, increased turbulence and modified depth profiles. Geomorphological consequences encompass sediment deposition, erosion, and alterations in river channel shape. The effects of biodiversity include blockage of fish passage, alterations in macroinvertebrate communities, and the degradation of riparian vegetation. Water quality is affected by local oxygenation, as well as the hazards of downstream stagnation and nutrient imbalance. Socio-ecological analysis uncovers trade-offs between energy accessibility and ecological integrity. Mitigation options encompass fish-friendly architecture, bypass channels, adaptive management and policy frameworks that mandate biological flows. Knowledge deficiencies remain in long- term ecological monitoring, sediment-nutrient interactions and socio-ecological integration. Innovative technologies, such as biomimetic blade designs and AI-driven monitoring, demonstrate potential for sustainable solutions. This review asserts that waterwheels can facilitate clean energy transitions if ecological protections are integrated into their design and control. A balanced strategy is crucial to optimize community advantages while preserving the integrity of river ecosystems.

Key words : Biodiversity, ecological impacts, river ecosystems, sustainable hydropower, waterwheel.

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INTRODUCTION

Rivers are lifelines for biodiversity, human well-being, and ecosystem services. They support drinking water, irrigation, fisheries, and cultural values. Hydropower has long been one of the most important renewable energy sources worldwide. Within hydropower, waterwheels and other small-scale technologies are considered low-impact options. They require modest infrastructure and can provide affordable energy to rural communities. However, even small hydropower structures can alter river ecology. It is timely to review their ecological impacts in detail.

Waterwheels differ significantly from large dams. They operate at low head and generally require little storage. Continuous river flow is usually maintained. This design reduces some of the fragmentation impacts seen in large reservoirs. Yet, waterwheels still change velocity, turbulence, and flow distribution in channels. Substrate disturbance and localized erosion can occur. These effects mean their ecological footprint is distinct but not negligible.

Proper ecological impact assessment (EcoIA) is essential. Without monitoring, the accumulation of small impacts across watersheds may become significant. The EcoIA helps to identify thresholds between natural variability and anthropogenic disturbance. In Indian rivers, researchers have emphasized this need for protecting lotic ecosystems and sustaining biodiversity (Srivastava, 2007).

The aim of this mini review is to synthesize current knowledge of ecological impacts from waterwheel installations on river ecosystems. Key areas include hydrology, geomorphology, biodiversity, water quality, and ecosystem services. The review also discusses mitigation strategies and highlights knowledge gaps. The goal is to promote eco-sensitive design and research that support both energy access and ecosystem health.

METHODOLOGY OF REVIEW

This review followed a structured literature search. Academic databases consulted included Scopus, Web of Science, and Google Scholar. Keywords used were "waterwheel," "pico hydro," "ecological impacts," "river ecosystems" and "biodiversity." To ensure broader coverage, peer-reviewed studies on hydropower and river ecology from national and international journals were considered (Benejam *et al*, 2016; Sharma *et al*, 2017; Srivastava, 2007; Xinxin *et al*, 2024; Amrita *et al*, 2024).

Studies were included if they examined ecological impacts of waterwheel or small hydropower installations. Both field assessments and modeling approaches were reviewed. Articles that focused only on engineering aspects without ecological evaluation were excluded.

The review emphasized literature published in the last two decades to capture contemporary developments. Older but influential works were included when essential for context. A major limitation was the small number of studies directly addressing traditional waterwheels. Most available research focused more broadly on small hydropower systems, requiring careful interpretation for waterwheel-specific impacts.

Hydrological and Geomorphological impacts

Hydrological impacts

Waterwheel installation changes river flow dynamics. Even small structures reduce local flow velocity and create turbulence zones. This alters depth distribution across the channel and modifies hydraulic habitats. Flow diversion for wheel operation can lower downstream discharge, especially during dry seasons (Sun *et al*, 2019). In tropical rivers, these changes influence seasonal flooding and connectivity with adjacent wetlands. Reduced flow also affects fish spawning grounds and aquatic vegetation, both of which depend on stable hydrological cycles (Rolls *et al*, 2012). Over time, flow alterations may modify nutrient availability and limit ecological resilience of river systems.

Geomorphological impacts

Hydrological shifts lead directly to geomorphological changes. Modified velocity alters sediment transport capacity, causing deposition upstream of structures and erosion downstream. This can create unstable riverbanks and simplify habitat structure. Channel morphology may shift toward less diverse forms, reducing habitat heterogeneity (Shi and Czerniawski, 2025). Shallow pools and riffles, essential for benthic fauna and fish, can be lost. In rivers with multiple installations, cumulative changes become more pronounced. These effects may fragment habitats and reduce ecosystem connectivity. Long-term alterations in riverbed structure threaten biodiversity and ecological services provided by dynamic river channels.

Impacts on Aquatic Biodiversity

Fish passage and migration

Waterwheels can act as partial barriers to fish movement. Although less obstructive than large dams, they still modify current and create turbulence zones. Small-bodied fish often struggle to navigate through or around wheel channels. Migratory species, such as carps and mahseers, common in Indian rivers, may face delays in upstream migration (Jaafar *et al*, 2021; Singh *et al*, 2010). Even if physical injury risk is lower than in turbine systems, repeated encounters across multiple installations can reduce reproductive success. Over time, these cumulative disruptions weaken fish populations and reduce genetic connectivity between river stretches.

Macroinvertebrates and benthic fauna

Alterations in flow and sediment transport strongly affect macroinvertebrate assemblages. Slower currents upstream of waterwheels favour taxa tolerant of depositional conditions. Sensitive groups such as Ephemeroptera, Plecoptera, and Trichoptera often decline near modified reaches (Tubiæ *et al*, 2024). Habitat simplification also reduces the richness of benthic communities. Since benthic invertebrates form a key food source for fish and amphibians, these shifts propagate up the food web. Reduced riffles and pools, which normally sustain high diversity, further diminish ecological stability.

Riparian vegetation and associated fauna

Impacts extend beyond aquatic habitats to riparian zones. Altered hydrology changes soil moisture and reduces overbank flooding. This affects germination, seed dispersal, and regeneration of riparian species. Vegetation decline decreases shading and organic matter input into the river, thereby weakening nutrient cycling. Fauna dependent on riparian vegetation, including insects, amphibians, and birds, also face habitat loss (O'Connell *et al*, 1993). With reduced connectivity between aquatic and terrestrial systems, the ecological role of riparian corridors is compromised.

Water quality and Ecosystem functioning

Temperature and oxygen dynamics

Waterwheels influence river water quality by altering physical and chemical conditions. The splashing effect of rotating paddles increases aeration. This can elevate dissolved oxygen concentrations, especially in shallow tropical rivers where oxygen depletion is common. Higher oxygen availability benefits fish, macroinvertebrates, and microbial communities. However, water diversion into wheel channels may reduce velocity downstream. Reduced flow can create stagnant pools that accumulate heat and organic matter. Such conditions increase temperature and reduce oxygen, leading to localized stress for aquatic organisms (Flow-MER, 2021; Shi and Czerniawsk, 2025). These contrasting outcomes demonstrate that the ecological consequences of waterwheels depend on site-specific flow regimes.

Nutrient cycling

Flow modification also alters nutrient transport and cycling. Reduced current velocity upstream favours deposition of organic matter and nutrients. Excess accumulation may lead to eutrophic conditions with algal growth. In contrast, reduced delivery of nutrients downstream can cause oligotrophic conditions. Both scenarios disturb microbial processing of carbon, nitrogen, and phosphorus. Disruption of nutrient cycling reduces primary productivity and alters energy transfer within food webs (Theis *et al*, 2022). Long-term imbalance weakens ecological stability and reduces resilience to disturbance.

Ecosystem services

Water quality changes directly affect ecosystem services. Increased oxygen from aeration can enhance self-purification processes, improving natural water treatment capacity. However, reduced downstream flow decreases water availability for riparian communities. Deterioration in quality undermines human use for drinking, irrigation, and domestic purposes. Fisheries productivity is also sensitive to oxygen and nutrient conditions (Rice and Garcia, 2011). Reductions in fish health or population abundance can undermine food security and diminish income sources for dependent communities (Cojocaru *et al*, 2022). These outcomes show that water quality shifts influence both ecological processes and socioeconomic well-being.

Socio-ecological Perspectives

Community benefits

Waterwheels provide decentralized electricity to rural households where grid access is limited. This supports lighting for study, evening activities, and community functions. Electricity also powers small enterprises such as sewing, rice milling and food processing. In India and Southeast Asia, pico-hydro adoption is common because of low cost and ease of local ownership (Lahimer *et al*, 2012; Williamson *et al*, 2020). Projects are often community- driven, with maintenance handled by local groups. These systems reduce reliance on diesel generators, lowering fuel expenses and greenhouse gas emissions. The result is improved livelihood opportunities and environmental sustainability at the village scale.

Trade-offs with ecology

Despite clear social gains, ecological costs persist. Flow diversion can lower water availability downstream, disrupting aquatic habitats. Waterwheels may obstruct fish migration and reduce riparian vegetation through altered hydrology. Such changes threaten biodiversity and affect subsistence fisheries. Local communities dependent on aquatic resources may lose food security and income. Thus, energy access creates trade-offs with ecological health (Arthur *et al*, 2022). Achieving balance requires careful project planning, integration of mitigation strategies and community engagement in environmental monitoring.

Alignment with sustainable development goals

Waterwheel projects align with several Sustainable Development Goals (SDGs). They contribute to SDG 7 by providing affordable clean energy and support SDG 13 by reducing carbon emissions. However, ecological risks challenge progress toward SDG 6, which emphasizes sustainable water resources and SDG 15, which focuses on biodiversity conservation (Department of Economic and Social Affairs (UN DESA), 2025; Herrera, 2019). Aligning projects with all relevant SDGs requires ecological safeguards. Incorporating fish-friendly designs, maintaining ecological flows, and promoting adaptive management help ensure that waterwheel electrification delivers social benefits without undermining river ecosystem integrity.

Mitigation and best practices

Design considerations

Eco-sensitive design is the first step to reducing ecological risks from waterwheels. Devices equipped with smooth paddles and low rotational speed limit direct harm to fish. Fish bypass channels or ladders can be integrated to support the connectivity of migratory species. Seasonal operation schedules are also important. Temporarily halting or reducing wheel activity during spawning seasons maintains ecological flows essential for reproduction and recruitment (King *et al*, 2009; Therrien and Bourgeois, 2000). Placement of wheels in non-critical habitats, away from spawning and nursery zones, further minimizes impacts.

Policy and regulation

Strong policy frameworks are critical for sustainable adoption. Environmental impact assessments should be mandatory for all new installations, regardless of scale. Regulatory authorities must set and enforce ecological flow requirements that preserve minimum discharge for aquatic organisms. Compliance monitoring ensures rules are implemented in practice (Altomonte, 2025). Involving local institutions in monitoring enhances both transparency and accountability (Shahi, 2023). Policy should also support cumulative impact assessments, since multiple small units can together exert large pressures on rivers.

Local knowledge and adaptive management

Incorporating community knowledge strengthens the resilience of projects. River-dependent communities hold detailed awareness of seasonal cycles, water levels, and fish behavior. Their participation in site selection, design, and long-term monitoring increases social acceptance and ecological performance (Verbrugge *et al*, 2017). Adaptive management frameworks are equally important. They allow operators to modify wheel operation based on ecological signals such as declining fish catches or changing flow conditions (Bradford *et al*, 2023). Combining science with traditional knowledge ensures waterwheels function in harmony with river ecosystems.

Knowledge gaps and Future directions

Limited long-term monitoring

Most existing research on waterwheel impacts is short term. Many studies focus on immediate hydrological or ecological responses observed over a few months or years. Long-term datasets that track river morphology, biodiversity, and ecosystem services remain scarce. This lack of continuity restricts understanding of cumulative effects that may emerge over decades (Turner *et al*, 2023). Monitoring programs are needed to evaluate how repeated flow changes and habitat modifications shape river ecosystems in the long run. Without such evidence, assessments may underestimate ecological risks.

Sediment and nutrient dynamics

Another major gap lies in sediment and nutrient research. Few investigations address how small-scale hydropower alters fluxes of suspended sediments or dissolved nutrients. This is particularly critical for tropical rivers where sediment transport supports fertile floodplains and agricultural productivity. Changes in sediment supply may also disrupt channel stability and riparian vegetation (Gumiero *et al*, 2015). Similarly, altered nutrient cycling can affect microbial processes, primary productivity, and fish food availability. Targeted field experiments and modeling studies are needed to clarify these linkages.

Socio-ecological integration

Most studies examine ecological or social outcomes separately. Very few adopt an integrated socio-ecological framework. These limits understanding of how community benefits and ecological risks interact. Combining ecological indicators with hydrological data and social surveys would provide more balanced insights for decision-making(Vollmer *et al*, 2018). Such integration is especially relevant in rural areas where livelihoods directly depend on rivers.

Technological innovations

Technological innovation offers a promising research frontier. Fish-friendly blade designs and biomimetic paddles can reduce ecological harm. The IoT-based sensors may enable real-time flow and biodiversity monitoring. Artificial intelligence can support automated analysis of ecological data, enhancing early detection of negative impacts. However, these tools remain underexplored in real river contexts (Martyszunis *et al*, 2024; Olawade *et al*, 2024). Future research should test their feasibility, cost- effectiveness, and ecological benefits in small hydropower projects.

CONCLUSION

Waterwheel installations represent a renewable and decentralized energy option. They provide clear community benefits but also pose ecological risks. Hydrological changes affect flow and sediment transport. Geomorphological impacts reshape channel features and habitats. Biodiversity is influenced through barriers to fish, shifts in macroinvertebrates, and riparian vegetation changes.

Water quality responses show both benefits and risks. Oxygenation may increase locally, yet downstream stagnation reduces water quality. Ecosystem services are altered in ways that affect both ecology and livelihoods. Socio-ecological perspectives highlight trade-offs between rural electrification and ecological integrity.

Mitigation measures such as fish-friendly design, bypass channels and adaptive management are promising. However, long-term monitoring remains limited. Research gaps include sediment flux, nutrient cycling, and socio-ecological integration. Emerging technologies such as biomimetic designs and AI-based monitoring tools provide new directions.

In conclusion, sustainable deployment of waterwheels requires balanced strategies. Policies must integrate ecological safeguards with community benefits. By addressing gaps and adopting best practices, waterwheels can contribute to clean energy goals without undermining river ecosystem health (Shiji *et al*, 2021).

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Author contributions statement

Izzatie Akmal Zulkarnain : Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & editing, Supervision, Project administration, Funding acquisition. **Mohd Farriz Basar :** Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Visualization.

Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author, [M.F.B], upon reasonable request. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

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