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A Review of the Impacts of Dam Construction on Regional Ecosystems

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Abstract:
With the increasing demand for water resources due to population growth and economic development, dams have become critical infrastructure for water supply, hydropower generation, and flood control. However, their construction and operation significantly alter natural river ecosystems, leading to habitat fragmentation, biodiversity loss, and other ecological challenges. This paper reviews recent research on the ecological impacts of dams, analyzing their effects through three dimensions: impact mechanisms, ecological responses, and mitigation strategies. Key findings reveal that dams disrupt hydrological processes, obstruct fish migration, and alter aquatic and terrestrial ecosystems, with regional variations in severity. For instance, the Three Gorges Dam has reduced fish spawning grounds, while dams in the U.S. have fragmented river habitats. Mitigation measures such as ecological flow releases, fish passage facilities, and watershed management can partially alleviate these impacts. The study underscores the need for balanced dam development that integrates socio-economic benefits with ecological conservation. By advancing scientific research and policy frameworks, sustainable water resource management can be achieved, minimizing irreversible damage to ecosystems.

Keywords: Dams, Ecological impacts; Hydrological alteration, Biodiversity loss; Mitigation strategies.

1. Introduction

With population growth and economic development, the demand for water resources continues to rise. Dams, as critical water infrastructure, play a key role in water supply, irrigation, hydropower generation, and flood control. However, dams alter the natural flow of rivers, leading to habitat fragmentation, biodiversity loss, sediment accumulation, and other issues that threaten ecosystem stability. For example, the 75,000 dams in the U.S. have a storage capacity close to the annual average runoff, with some regions storing more than three times the annual runoff, significantly altering hydrological and ecological processes [1].

The ecological impacts of water resource development vary significantly across regions. In the southwestern U.S., dam storage far exceeds annual runoff, resulting in more severe ecological consequences, whereas impacts are relatively milder in the northeastern U.S. Dams hold substantial socio-economic value, providing electricity as a crucial source of clean energy, especially in developing countries. They ensure stable irrigation and drinking water supplies, supporting agricultural and urban development, and can mitigate flood risks by regulating runoff.

However, dams also generate considerable ecological controversy. They obstruct fish migration, leading to species decline—for instance, the Three Gorges Dam on the Yangtze River has affected the habitats and reproduction of multiple fish species [2]. Reduced or altered downstream flow impacts wetlands and vegetation, as seen in the shrinking wetlands along the lower Colorado River due to dams. Additionally, dams may submerge cultural heritage sites and displace communities, sparking social conflicts.

Given the profound impact of dams on human life, despite extensive research, the effects on ecological components such as phytoplankton, benthic organisms, and microbes remain insufficiently understood. Most studies focus on single species or short-term effects, lacking systematic assessments of cascading dams and long-term ecological responses. Scientific data are essential for formulating sustainable water resource policies before research begins. For example, optimizing dam operations (e.g., ecological flow releases) can mitigate ecological harm.

The construction and operation of dams require balancing socio-economic benefits with ecological conservation. Strengthening scientific research, improving policy frameworks, and advancing technological innovation can promote sustainable water resource development while minimizing irreversible damage to ecosystems. The urgency of current research demands a more comprehensive understanding of dams' ecological impacts to provide a scientific basis for future water resource management.

This paper aims to review recent domestic and international research on the ecological impacts of dams, analyzing them through three dimensions—impact mechanisms, ecological responses, and mitigation strategies—to clarify current progress and challenges. It also proposes future research directions and recommendations for sustainable dam development.

2. Overview of Dam Engineering Types and Regional Ecosystems

2.1 Overview of Dam Engineering Types and Regional Ecosystems

Dams can be classified into several categories based on their structure, function, and construction materials. Gravity dams resist water pressure through their own weight and are typically made of concrete or masonry, offering high stability. A prominent example is China's Three Gorges Dam, which has a large storage capacity and significantly alters downstream hydrology. Arch dams feature a curved design that distributes water pressure through arch mechanics and are suitable for narrow canyons. The Hoover Dam in the U.S. is a classic example, though it exerts substantial impacts on local geology and river morphology. Embankment dams constructed from loose materials like earth and rock are cost-effective and adaptable. The Aswan High Dam in Egypt is a well-known case, though it faces severe siltation issues that disrupt downstream sediment transport. Pumped-storage hydropower plants store water during low electricity demand and release it during peak periods to balance grid loads. An example is China's Tianhuangping Pumped-Storage Power Station, which has minimal impact on aquatic ecosystems but raises concerns over energy consumption. Other less common types include buttress dams like Brazil's Itaipu Dam and rubber dams used in small-scale projects with minor ecological effects [3].

2.2 Geographic and Watershed Characteristics of Dam Distribution

Dam distribution is shaped by both natural conditions and socio-economic demands. Mountainous and canyon regions such as the upper Yangtze and Colorado River often host high dams with large reservoirs that maximize hydropower benefits but disrupt fish migration and longitudinal river connectivity. Plains and lowland rivers like the Mississippi and lower Yellow River primarily feature low dams for flood control and irrigation, leading to wetland shrinkage, reduced sediment deposition, and delta degradation. Arid and semi-arid regions including the Nile and Indus River rely on reservoirs for agricultural water regulation, but this can cause downstream ecological water shortages as seen in salinization of Egypt's Nile Delta. Tropical rainforest zones like the Amazon and Mekong River have seen recent dam projects with major ecological controversies such as Brazil's Belo Monte Dam, resulting in forest flooding, biodiversity loss, and impacts on indigenous communities.

2.3 Key Components of Regional Ecosystems Affected by Dams

Dams influence ecosystems that typically include river systems, wetlands, forests, and human activities. River systems that provide water flow, sediment transport, and habitat provision are affected through reduced flow velocity, thermal stratification, and altered benthic communities.

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Wetlands that support water purification, biodiversity, and carbon sequestration shrink in area as seen in lakes downstream of the Three Gorges Dam. Forests vital for soil conservation and climate regulation are lost to reservoir flooding, exemplified by Amazon rainforest deforestation due to hydropower dams [4]. Human activities including agriculture, fisheries, and urban water supply face impacts from reduced fish stocks like the Mekong River fisheries decline and resettlement conflicts.

2.4 Ecosystem Sensitivity and Coupling Mechanisms

Dam impacts on ecosystems are cumulative and cascading. Hydrological changes eliminate natural flood pulses that disrupt fish spawning, while thermal stratification in deep reservoirs releases cold water that harms downstream aquatic life as seen in salmon decline in the U.S. Columbia River. Sediment trapping leads to reservoir siltation and downstream riverbed erosion, causing delta retreat as observed in the Nile Delta. Species migration barriers block fish passages, nearly driving the Chinese sturgeon to extinction due to the Gezhouba Dam. Still waters favor invasive species proliferation like water hyacinth in African reservoirs. Transboundary conflicts arise from upstream water storage, while wetland degradation reduces flood mitigation and water purification capacities. The ecological impact intensity depends on dam type and location, while regional ecosystem sensitivity determines recovery difficulty. Through scientific planning and policy optimization, we can minimize irreversible damage and enable sustainable water resource development.

3. Major Impacts of Dam Construction on Regional Ecosystems

3.1 . Alteration of Hydrological Processes

The construction and operation of dams significantly modify the natural hydrological processes of rivers, affecting flow volume, velocity, seasonal rhythms, and flood mechanisms. These changes not only impact the rivers themselves but also have far-reaching consequences for surrounding ecosystems, climate patterns, and human societies.

First, dams alter flow volume, velocity, and direction. Natural river flows typically fluctuate with precipitation, snowmelt, and other natural processes, whereas dams artificially regulate flow through water storage and release, making it more stable or adjusting it for purposes such as power generation and irrigation. In cold regions, dams often increase water release in winter to meet electricity demand (e.g., heating), resulting in higher downstream flows than under natural conditions [5]. Conversely, dams store water in spring to prepare for summer droughts or power generation needs, reducing downstream flow and affecting fish spawning and riparian vegetation growth. By intercepting floods, dams reduce peak discharge downstream, decreasing the frequency of natural flooding and disrupting nutrient cycling in floodplain ecosystems. Additionally, dams may release excess water during dry seasons, elevating low-flow levels above natural baselines and disturbing species adapted to such conditions. Dams also result in reduced upstream flow velocity and unstable downstream flow. After reservoir impoundment, upstream river sections shift from flowing water to a stagnant environment, significantly slowing flow velocity and causing sediment deposition (e.g., silt and organic matter), thereby degrading water quality and benthic habitats. Dam releases may cause erratic downstream flow fluctuations—such as pulsed discharges due to power generation needs (e.g., daytime releases for electricity and reduced flow at night)—disrupting aquatic organisms' adaptability. Many dams are accompanied by diversion channels or interbrain water transfer projects, redirecting portions of river flow to other regions and reducing or even cutting off flow in the original river sections (e.g., the Yellow River's downstream drying up due to excessive diversions). Natural rivers recharge groundwater through lateral seepage, but dam-regulated reductions in downstream flow may lower groundwater recharge rates, affecting riparian vegetation and wetland ecosystems.

Second, dams disrupt seasonal rhythms and eliminate natural flooding mechanisms. Temperate and boreal rivers typically follow a pattern of spring snowmelt floods (high flow), summer stability, autumn rainfall recharge, and winter low flow. Tropical rivers, influenced by monsoons, exhibit high flow during wet seasons and low flow during dry seasons. Dams cause rhythm inversion or homogenization—for example, increasing winter flow in Quebec, Canada, where dams release more water to meet heating demands. Reduced spring flow due to dam storage weakens snowmelt floods downstream, disrupting fish migration and riparian vegetation germination. In tropical regions, dams may diminish wet-season floods and increase dry-season flow, altering the adaptive mechanisms of river ecosystems. Natural floods are critical for nutrient replenishment and habitat renewal in riparian ecosystems. The loss of natural flooding mechanisms significantly impacts ecology: after dams intercept floods, downstream floodplain ecosystems degrade, and biodiversity declines. Dam construction also modifies local climate. Increased reservoir evaporation raises air humidity, potentially altering precipitation patterns, particularly in arid and semi-arid regions (e.g., Mediterranean climates). Large reservoirs may reduce temperature fluctuations (cooling in summer, warming in winter), affecting agricultural growth cycles. Additionally, enhanced moisture from reservoirs may intensify convective activity, increasing the frequency of localized heavy rainfall or thunderstorms [6].

3.2 Impacts on Aquatic Ecosystems

The most significant impact of dams is the obstruction of fish migration routes and population degradation. Dam construction disrupts upstream and downstream migration pathways, affecting fish reproduction and survival. For example, the Three Gorges Dam on the Yangtze River has reduced spawning grounds for migratory fish such as the Chinese sturgeon, leading to population declines. Cascade dam development exacerbates habitat fragmentation, isolating fish populations, reducing genetic diversity, and increasing the risk of local extinction. The discharge of cold water from deep reservoir layers can delay fish spawning and inhibit juvenile growth, further threatening population recovery. In the Yangtze River basin, the "Four Major Chinese Carps" (black carp, grass carp, silver carp, and bighead carp) rely on river-lake connectivity for reproduction and growth. Dam construction has reduced migration pathways (e.g., only four remain between Dongting Lake and the Yangtze) and drastically shrunk spawning grounds (an 85% decline in fish egg production from the 1960s to 1981) [7]. In the Paraná River Basin, migratory fish (e.g., *Prochilodus lineatus*) have suffered sharp population declines due to shortened flood periods (<75 days), drastically reducing juvenile survival rates [8]. In U.S. rivers, 79% of river segments are isolated from estuaries by dams, causing significant declines in long-distance migratory fish (e.g., salmonids) [9].

Dam reservoirs slow water flow, leading to nutrient accumulation and algal blooms (e.g., cyanobacteria), causing eutrophication. The reservoir's retention effect prolongs water residence time, promoting sediment adsorption of nutrients, while weakened flood pulses reduce organic matter input from floodplains, altering primary productivity distribution. Thermal stratification exacerbates bottom-layer hypoxia, triggering anaerobic bacteria to release phosphorus and creating a vicious cycle. Still-water environments replace flowing-water habitats, favoring planktonic species (e.g., certain phytoplankton) while reducing flow-dependent species (e.g., benthic invertebrates), significantly altering ecological niches. Sediment trapping by dams reduces downstream nutrients, affecting benthic organisms and plant growth, further restructuring food webs. In the Yangtze Basin, regulated lakes like Dongting Lake experience reduced water exchange, nutrient retention, and increased algal bloom risks. Upstream reservoirs in the Paraná River weaken flood pulses, reducing submerged vegetation decomposition and nutrient input, disrupting benthic food webs. U.S. reservoirs, particularly in agricultural regions (e.g., the Mississippi Basin), frequently suffer from eutrophication and cyanobacterial blooms due to nitrogen and phosphorus accumulation.

Dam reservoirs submerge terrestrial vegetation, while downstream water-level fluctuations alter riparian plant distribution—expanding some species (e.g., reeds) while reducing others (e.g., submerged plants). Wetland vegetation changes affect bird habitats and food sources, leading to declines in migratory bird populations. Dams reduce fungal and benthic invertebrate diversity in water bodies, while downstream lake soil microbes may increase due to sediment changes. Habitat homogenization (e.g., loss of rapids) excludes specialized species, favoring generalists. Reservoir inundation eliminates natural riparian vegetation, transforming gravel substrates into silt, causing spawning failure for gravel-dependent fish (e.g., salmonids). Additionally, invasive species (e.g., tilapia) expand in reservoirs, intensifying competition with native species. In the mid-Yangtze, fish communities have shifted from over 20 diverse dominant species to a simplified structure dominated by bottom-dwelling fish (e.g., bronze gudgeon), with the "Four Major Carps" declining from 80% in the 1950s to less than 10% today. In the Paraná Basin, migratory fish biomass correlates with flood duration, with juvenile numbers dropping 90% in dry years. In U.S. rivers, flow-dependent fish (e.g., trout) have declined 30%-50% below dams, while still-water species (e.g., sunfish) have increased.

3.3 Terrestrial Ecology and Land-Use Changes

The construction of the Three Gorges Dam, for instance, has profoundly altered surrounding terrestrial ecosystems and land-use patterns. Following reservoir impoundment, rising water levels permanently submerged approximately 1,080 km² of land, directly destroying original riparian vegetation and terrestrial ecosystems. Studies indicate that 400-770 vascular plant species lost their habitats due to inundation, with endemic species such as Myricaria laxiflora nearly extinct in the wild [10]. Some flood-tolerant species (e.g., Salix variegata, Polygonaceae) survived by migrating to higher elevations, but most plants disappeared locally due to their inability to adapt to unnatural winter flooding (historically, flooding occurred in summer). This led to the formation of barren drawdown zones. Additionally, the reservoir fragmented once-continuous natural habitats, obstructing wildlife migration and genetic exchange, further accelerating biodiversity loss.

The reservoir area, already impacted by long-term agricultural development, saw further degradation of secondary forests due to increased erosion and landslide

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risks post-impoundment. Forests on steep slopes became more prone to collapse as soil moisture saturation rose, leading to sustained declines in vegetation cover. Natural seasonal floodplain wetlands were replaced by artificial water-level regulation, causing the decline of original wetland plant communities due to altered hydrological rhythms. The newly formed drawdown zones, subjected to frequent water fluctuations and erosion, now support only a few drought-resistant herbs, with significantly reduced biomass. High population density around the reservoir exacerbated pressures from agricultural expansion, logging, and pollution (e.g., direct sewage discharge), further accelerating the degradation of forests and grasslands and weakening ecosystem resilience.

The Three Gorges Project has reconfigured regional terrestrial ecology through direct inundation and indirect hydrological modifications. In the short term, habitat loss and fragmentation have driven biodiversity decline. Over the long term, the combined effects of hydrological regulation and human activities may trigger more extensive ecosystem degradation.

4. Ecological Regulation and Environmental Management Strategies

The impacts of dam construction on aquatic ecosystems are cumulative and long-term. However, through scientific ecological regulation and environmental management strategies, negative effects can be partially mitigated, promoting sustainable watershed development.

4.1 Restoration of Fish Migration Pathways and Population Conservation

Ecological flow regulation plays a crucial role and can simulate natural hydrological rhythms by releasing artificial flood peaks during fish breeding seasons (such as May-June in the Yangtze River) to stimulate fish spawning. Maintaining minimum ecological flows is essential for ensuring adequate water volume in downstream river sections to support fish survival, as exemplified by the requirements for salmon migration flows in the Columbia River Basin under the U.S. Endangered Species Act. Fish passage facilities are considered optimal solutions for most dams. Fish ladders are suitable for low to medium-height dams and support the upstream migration of certain species, while fish lifts, appropriate for high dams like the Three Gorges Dam, mechanically transport fish across barriers. Artificial breeding and stocking programs can supplement wild populations of endangered species through captive propagation and release. Following environmental disturbances, habitat restoration should be implemented, including reconnecting floodplains, removing obstructive barriers to enhance river-lake connectivity, and optimizing reservoir operation modes. For instance, reservoirs in the upper Paraná River maintain higher water levels during summer to simulate natural flooding, facilitating juvenile fish access to floodplain feeding grounds.

4.2 Control of Water Eutrophication and Water Quality Improvement

Reservoir operation optimization is of paramount importance, with selective withdrawal being a common approach - drawing water from reservoir surface layers during summer to reduce discharge of cold, oxygen-depleted water and suppress algal blooms. Balancing reservoir storage with downstream ecological needs involves increasing discharge during high eutrophication risk periods (such as summer) to enhance water exchange. Comprehensive watershed management should focus on reducing non-point source pollution by promoting ecological agriculture and minimizing fertilizer and pesticide inputs, as demonstrated by the rice-fish co-culture model adopted in the middle Yangtze agricultural regions. Constructing wetlands at reservoir tributary inlets or dam forebay areas can effectively filter nitrogen and phosphorus, while environmental dredging should be conducted in severely eutrophicated reservoir zones, complemented by submerged vegetation planting to improve water quality.

4.3 Biodiversity Conservation

The establishment of ecological protected areas has become widespread, such as the “Four Major Chinese Carps National Aquatic Germplasm Resources Conservation Zone” in the upper Yangtze River where shipping and fishing activities are restricted. Additionally, removing small abandoned dams can restore rapid-deep pool structures and enhance benthic organism and fish diversity. To maintain local ecological balance, strengthened quarantine measures and monitoring systems are necessary to prevent the escape of invasive species like tilapia and mosquitofish through shipping or aquaculture activities. For existing invasions, introducing native dominant species in affected river reaches can intensify niche competition. Current technological advancements significantly contribute to ecological protection, including the application of remote sensing and eDNA technologies for monitoring fish population dynamics (as exemplified by multiple aquatic ecological monitoring stations deployed along the Yangtze River). Management strategies should be dynamically adjusted based on environmental and rainfall data, similar to the Paraná River’s approach of modifying reservoir discharge plans according to annual rainfall predictions to optimize flood pulse timing.

4.4 Policy Framework and Public Participation

Regulatory safeguards are fundamentally important, requiring the establishment of ecological compensation mechanisms where hydropower enterprises contribute to ecological restoration funds. For transboundary rivers, watershed management agreements should be negotiated to coordinate hydropower and ecological requirements. Beyond government actions, public and community engagement generates substantial influence: ecological education programs can enhance public awareness of river ecosystems and encourage citizen monitoring of water quality. In regions dependent on aquatic environments, supporting fishermen in occupational transition (such as developing ecotourism or aquaculture) can reduce reliance on wild fish stocks.

The ecological impacts of dams cannot be completely eliminated, but through an integrated governance model combining "engineering measures + ecological restoration + policy management", negative effects can be significantly reduced. Future efforts should emphasize interdisciplinary research (encompassing ecohydrology and fish ethology) and intelligent management systems (such as AI-based prediction of fish migration periods) to achieve a balance between hydropower development and ecological conservation.

5. Conclusion

Dam construction significantly alters regional ecosystems through hydrological changes, habitat fragmentation, and biodiversity loss, yet remains indispensable for water resource management and socio-economic development. This review synthesizes evidence that dams disrupt natural flow regimes, obstruct fish migration, and modify aquatic and terrestrial ecosystems, with impacts varying by dam type (e.g., gravity vs. arch dams) and geographic context (e.g., arid vs. tropical regions). Cascade dams exacerbate ecological degradation, while sediment trapping and thermal stratification further destabilize downstream ecosystems. Mitigation strategies—such as ecological flow releases, fish passage facilities, and watershed management—demonstrate partial efficacy in restoring ecological functions.

The study underscores the urgency of balancing hydropower development with ecosystem conservation through interdisciplinary approaches. By integrating scientific research, policy optimization, and technological innovation, future dam projects can minimize irreversible ecological harm while meeting human needs. This work provides a foundation for sustainable water resource governance and highlights critical gaps in long-term ecological monitoring, particularly for microbial and benthic communities.

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