



Impacts of Civil Infrastructure and Dam Structures on Aquatic Ecosystems: A Comprehensive Survey of Hydrological, Geomorphological, and Biodiversity Responses

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Abstract:

Civil-construction activities and hydraulic structures such as dams, reservoirs, embankments, bridges, culverts, river-training works, and water-diversion systems are essential for urban development, flood management, irrigation, navigation, and energy production; however, their construction and operation can substantially modify the physical, chemical, and biological processes governing aquatic ecosystems. The principal ecological consequences arise from alteration of natural flow regimes, sediment transport, channel morphology, water temperature, nutrient dynamics, habitat connectivity, and pollutant pathways. Dams are particularly influential because they transform flowing riverine environments into comparatively lentic reservoir systems while simultaneously disrupting longitudinal connectivity between upstream and downstream habitats. Global assessments indicate that dams and reservoirs are among the dominant anthropogenic pressures responsible for river fragmentation, with major implications for freshwater biodiversity. This review synthesizes major scientific findings concerning the effects of civil-construction and dam structures on aquatic ecosystems, with particular emphasis on hydrological modification, sediment retention, habitat fragmentation, water-quality deterioration, fish migration, and biodiversity. The discussion further considers ecological-flow management, fish passage, sediment-management strategies, environmentally sensitive construction practices, and removal or modification of obsolete structures as potential mitigation measures. The review demonstrates that sustainable hydraulic infrastructure requires an integrated engineering–ecological framework in which structural functionality and ecosystem integrity are considered simultaneously during planning, design, construction, and operation.

Keywords: Aquatic ecosystems; civil construction; dams; reservoirs; river fragmentation; ecological flow; sediment transport; aquatic biodiversity; fish migration; sustainable infrastructure.

Introduction

Freshwater ecosystems constitute highly dynamic environmental systems in which hydrology, geomorphology, water chemistry, biological communities, and sediment processes interact continuously. Rivers and associated wetlands provide essential ecological services, including habitat provision, nutrient cycling, sediment transport, groundwater recharge, fisheries production, and maintenance of biodiversity. Nevertheless, increasing urbanization, industrialization, agricultural development, and infrastructure expansion have resulted in extensive modification of natural watercourses. Civil-construction activities can directly disturb river channels and riparian zones through excavation, embankment construction, bridge and culvert installation, channelization, bank protection, and temporary diversion of flows. Such interventions may alter hydraulic conditions, increase suspended sediment concentrations, disturb benthic habitats, and reduce the ecological complexity of river systems. Dams represent a particularly significant category of hydraulic infrastructure because their effects extend beyond the immediate construction site and can propagate throughout upstream reservoirs, downstream river reaches, floodplains, estuaries, and, in some cases, adjacent coastal environments. Poff and Hart (2002) emphasized that dams modify the magnitude and timing of downstream water movement, while subsequent research has demonstrated that these hydrological alterations can substantially influence the structure and functioning of river ecosystems.

The ecological consequences of infrastructure development are not necessarily uniform because they depend on dam height, reservoir volume, operational regime, river morphology, climatic conditions, sediment characteristics, biological assemblages, and the cumulative effects of multiple structures within a watershed. Grill et al. (2019) demonstrated the global significance of this problem by showing that only approximately 37% of rivers longer than 1,000 km remain free-flowing over their entire length, with dams and reservoirs identified as major contributors to river fragmentation and loss of connectivity. Consequently, the environmental assessment of civil infrastructure should extend beyond localized construction impacts and incorporate watershed-scale changes in ecological connectivity and ecosystem processes.

Literature Review

The early contribution of Poff and Hart (2002) was particularly important because it demonstrated that dams cannot be treated as a homogeneous category of infrastructure. Differences in dam size, operating mode, age, storage capacity, and watershed characteristics determine the magnitude and nature of ecological disturbance. Similarly, Hart et al. (2002) shifted attention toward dam removal as a potential river-restoration strategy and emphasized that ecological responses

involve interacting physical, chemical, and biological processes rather than a single environmental variable. Their work showed that removal may restore lotic conditions but can also initiate substantial sediment redistribution and temporary habitat disturbance.

A major conceptual development occurred with the global assessment of Nilsson et al. (2005), which demonstrated extensive fragmentation and flow regulation of the world's large river systems. This work established that dams represent a landscape-scale disturbance rather than an isolated hydraulic intervention. Subsequently, the ecological-flow framework developed by Poff et al. emphasized that ecosystem integrity depends not merely on the quantity of water released downstream but also on the natural variability of flow magnitude, frequency, duration, timing, and rate of change.

The scope of research expanded considerably with Vörösmarty et al. (2010), who assessed threats to river biodiversity and human water security at a global scale. Their analysis demonstrated that river ecosystems are subjected simultaneously to multiple stressors, including flow regulation, water abstraction, pollution, and habitat alteration. This was an important progression from single-impact dam studies toward multi-stressor analysis.

During the middle and latter portions of the study period, increasing attention was given to the geographical distribution of dam-related ecological research. Branquinho and Brito (2016) found that scientific studies concerning dams and biodiversity were disproportionately concentrated in temperate regions, even though substantial future hydropower development was anticipated in tropical regions containing exceptionally high levels of biodiversity. This geographic imbalance indicates that existing scientific knowledge may not adequately represent ecological responses in tropical and subtropical river systems.

By 2018, research had begun to incorporate ecosystem metabolism and biogeochemical processes more explicitly. Studies of dam effects on biogeochemical cycling identified changes in water circulation, hydraulic residence time, sedimentation, nutrient retention, nutrient transformation, greenhouse-gas processes, and biological communities. This indicated that dams influence aquatic ecosystems not only through physical habitat modification but also through alteration of fundamental ecosystem processes.

In the same year, Grill et al. (2019) provided a major global-scale assessment of river connectivity. Their analysis of approximately 12 million kilometres of rivers showed that only 37% of rivers longer than 1,000 km remained free-flowing along their entire length, demonstrating the extensive influence of infrastructure on global river connectivity. Collectively, these studies demonstrate a clear evolution in research: from dam-specific physical impacts → hydrological alteration → habitat fragmentation → biodiversity impacts → global connectivity → integrated ecosystem processes.

Overall, the literature indicates that the environmental influence of civil-construction and dam structures is multidimensional. The earliest studies primarily characterized physical and hydrological modifications, including changes in discharge, sediment transport, channel morphology, and connectivity. Subsequent studies increasingly examined ecological consequences, particularly effects on fish, benthic organisms, plankton, microorganisms, riparian vegetation, and birds. By the end of the period, research had progressed toward global-scale connectivity assessment and ecosystem-process analysis.

However, there remains a substantial imbalance between studies that document ecological responses and studies that quantitatively establish cause–effect relationships between engineering design/operation parameters and ecological outcomes. In particular, dam height, reservoir volume, spillway configuration, turbine operation, sediment-management strategy, environmental-flow characteristics, and cumulative dam density are rarely incorporated simultaneously into predictive ecological models. The literature therefore provides strong evidence that dams affect aquatic ecosystems but is less developed in determining which engineering parameters produce specific ecological thresholds and how infrastructure can be optimized to minimize ecological degradation.

Comparative Assessment

Author(s) and Year	Principal Research Focus	Major Findings	Methodological Emphasis	Major Limitation / Unresolved Issue
Poff & Hart (2002)	Dam characteristics and ecological consequences	Demonstrated that dam size, age, operation, storage, and location strongly influence downstream ecological responses.	Conceptual ecological classification of dams	Limited quantitative prediction of ecosystem response for specific dam configurations.
Hart et al. (2002)	Dam removal and river restoration	Demonstrated that dam removal can restore natural river processes but may initially produce sediment-related disturbances.	Interdisciplinary physical, chemical, and biological assessment	Long-term ecosystem responses and transferability among river systems remained uncertain.
Nilsson et al. (2005)	Global river fragmentation and flow regulation	Demonstrated extensive fragmentation and regulation of large river systems by dams and other infrastructure.	Global-scale spatial assessment	Biodiversity responses were less comprehensively quantified than physical

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				fragmentation.
Poff et al. (2007)	Ecological flow and river restoration	Established the importance of maintaining natural flow variability for ecosystem integrity and restoration.	Ecological-flow framework	Practical implementation of environmental-flow regimes remains site-specific.
Vörösmarty et al. (2010)	Freshwater ecosystem degradation	Demonstrated that river systems are exposed to multiple interacting pressures including flow regulation, pollution, water abstraction, and habitat modification.	Global comparative analysis	Limited representation of local ecological processes and species-specific responses.
Branquinho & Brito (2016)	Global dam–biodiversity research trends	Found that research was geographically biased toward temperate regions despite substantial future dam development in highly biodiverse tropical regions.	Scientometric analysis	Research-output patterns do not directly quantify ecological damage.
Zarfl et al. (2015)	Future global hydropower expansion	Demonstrated the large potential scale of future dam development and associated river fragmentation.	Global infrastructure inventory and scenario analysis	Future projections contain uncertainties concerning construction, cancellation, and operational changes.
Wu et al. (2019)	Comprehensive biodiversity effects of dams	Synthesized 347 publications from 2000–2017 and identified effects on microorganisms, benthos, plankton, fish, plants, and birds.	Systematic literature review	Considerable heterogeneity among studies and insufficient long-term, multi-trophic investigations.
Grill et al. (2019)	Global free-flowing rivers	Demonstrated that only about 37% of rivers longer than 1,000 km remain free-flowing over their entire length, highlighting the global significance of infrastructure-induced fragmentation.	Global GIS/spatial connectivity analysis	Primarily focused on river connectivity indicators rather than detailed biological mechanisms.
Chen et al. (2020 and preceding studies)	Dam-induced river ecosystem alteration	Increasingly emphasized interactions among hydrology, sediment, habitat, water quality, and aquatic organisms.	Integrated ecological and environmental assessment	Need for standardized indicators and predictive models across climatic and geographic regions.

Research Gap

Despite substantial research between 2000 and 2020, several important research gaps remain. First, much of the existing literature has examined individual environmental components separately, such as flow, sediment, fish, water quality, or biodiversity. The interactions among these variables remain insufficiently quantified. Since aquatic ecosystems respond to coupled hydrological, hydraulic, geomorphological, chemical, and biological processes, future investigations require integrated rather than single-factor assessment frameworks.

Second, there is a significant scale mismatch between engineering studies and ecological studies. Civil-engineering investigations frequently concentrate on dam hydraulics, structural safety, reservoir operation, sedimentation, and water-storage performance, whereas ecological studies focus on species abundance, habitat condition, biodiversity, or ecosystem processes. Relatively few studies integrate these two perspectives into a common engineering–ecological modelling framework.

Third, although global research has demonstrated extensive river fragmentation, there is insufficient quantitative understanding of the relationship between dam characteristics and ecological thresholds. For example, additional research is required to determine how dam height, hydraulic head, reservoir residence time, downstream flow variability, sediment trapping efficiency, and operational fluctuations influence fish migration, macroinvertebrate communities, aquatic vegetation, and overall biodiversity.

Fourth, research remains geographically uneven. Branquinho and Brito (2016) specifically identified a concentration of

biodiversity-related dam research in temperate regions, whereas tropical and subtropical systems remain comparatively underrepresented. This is particularly important for countries such as India, where river systems experience simultaneous pressures from dams, irrigation structures, urbanization, industrial development, sand mining, pollution, and climate variability.

Fifth, relatively few investigations have adequately addressed cumulative and cascading effects of multiple dams within the same river basin. A single dam may have a measurable local effect, but a sequence of reservoirs can alter an entire river network by progressively modifying flow, sediment, temperature, nutrient transport, and biological connectivity. Global studies have demonstrated the importance of this cumulative fragmentation problem, but detailed ecosystem-response models remain limited.

Sixth, long-term datasets remain insufficient. Many investigations are based on short-term monitoring before and after dam construction or removal. Such datasets may fail to capture delayed ecological responses, adaptation, species replacement, trophic restructuring, and cumulative sedimentation effects. The absence of standardized long-term monitoring also makes comparison among different river systems difficult.

Finally, existing environmental-flow research often focuses on defining minimum discharge requirements rather than reproducing the full ecological characteristics of natural flow regimes. Future research should therefore investigate flow magnitude, timing, duration, frequency, rate of change, temperature, sediment transport, and flood-pulse characteristics simultaneously.

Conclusion

Civil-construction activities and dam structures provide substantial societal benefits, but their environmental consequences demonstrate that hydraulic infrastructure cannot be evaluated solely according to structural performance, water-storage capacity, flood protection, or energy production. Dams and associated construction activities modify hydrological regimes, sediment transport, thermal conditions, channel morphology, nutrient dynamics, habitat connectivity, and biological migration pathways, thereby influencing aquatic biodiversity at local, regional, and watershed scales. The literature consistently indicates that river fragmentation and alteration of natural flow regimes are among the most important mechanisms responsible for ecological degradation.

Sustainable infrastructure development should therefore incorporate environmental-flow requirements, sediment continuity, aquatic organism passage, riparian protection, ecological monitoring, and cumulative watershed assessment from the earliest planning stage. Future research should increasingly integrate hydraulic modelling, geomorphology, ecological indicators, remote sensing, environmental DNA, artificial intelligence, and long-term field monitoring to quantify infrastructure-induced ecological changes and optimize mitigation measures. Ultimately, the objective should not be to eliminate civil infrastructure but to develop ecologically compatible hydraulic systems in which engineering functionality and aquatic ecosystem integrity are treated as complementary design requirements.

Future Scope

Future research should move toward the development of an integrated Eco-Hydraulic–Civil Engineering Assessment Framework capable of linking infrastructure characteristics with aquatic ecosystem responses. Such a framework could combine hydrodynamic modelling, sediment-transport modelling, ecological habitat simulation, biodiversity indicators, and water-quality modelling. Numerical models such as HEC-RAS, MIKE, Delft3D, TELEMAC, SWAT, and other coupled hydrological–ecological platforms could be integrated with field observations to predict downstream ecological responses under alternative dam-operation scenarios.

A particularly promising research direction is the development of environmental-flow optimization models. Instead of defining a single minimum release, optimization algorithms could determine flow regimes that simultaneously satisfy irrigation, hydropower, flood-control, water-supply, and ecological requirements. Multi-objective optimization, evolutionary algorithms, and machine-learning approaches could be used to identify operational strategies that minimize ecological damage while maintaining infrastructure functionality.

Future studies should also investigate sediment continuity and ecological sediment management. Reservoir sedimentation should be evaluated not only as a loss of storage capacity but also as a disruption of downstream geomorphological and ecological processes. Sediment flushing, sluicing, bypass systems, controlled sediment release, and engineered sediment replenishment should be evaluated through coupled hydraulic and ecological models.

Another important area is AI- and data-driven aquatic ecosystem prediction. Machine-learning and deep-learning models can potentially establish relationships between dam operation, discharge, water temperature, turbidity, dissolved oxygen, sediment concentration, habitat characteristics, and biological indicators. Remote sensing, satellite imagery, drone-based surveys, environmental DNA (eDNA), automated acoustic monitoring, and sensor networks could provide high-frequency ecological observations. These data could be incorporated into predictive models for early identification of ecological degradation.

Future research should additionally address climate change–dam interactions. Changes in precipitation patterns, drought frequency, extreme floods, temperature regimes, evaporation, and sediment yield may modify the ecological consequences of existing dams. Consequently, reservoir operation strategies developed under historical climatic conditions may not remain environmentally optimal under future climate scenarios.

The concept of digital twins for river infrastructure represents another promising research direction. A digital twin could integrate real-time dam operation, hydrological conditions, water quality, sediment transport, aquatic habitat, and biodiversity information into a dynamic computational representation of the river system. Such a platform could allow

engineers and environmental managers to test alternative operational scenarios before implementing them in the field. Finally, future research should emphasize nature-based and hybrid engineering solutions. Instead of relying exclusively on conventional concrete structures, river restoration could incorporate nature-like fishways, constructed wetlands, riparian buffers, environmental-flow channels, sediment bypass systems, engineered floodplains, and eco-hydraulic bank protection. These approaches could provide hydraulic and structural functionality while simultaneously improving habitat quality and ecological connectivity.

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