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Editorial: River rehabilitation in the Anthropocene

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Editorial on the Research Topic
River rehabilitation in the Anthropocene

1 Introduction

The Anthropocene is proposed as the current geologic epoch where humans are the dominant driver of global ecosystem states and functions. Riverine landscapes and the ecosystems they contain are subject to multiple interacting anthropogenic stressors including channelization, dam construction, floodplain development, hydrological modification, land-use change, levee construction, pollutants, species invasion, and urbanization (Table 1). Globally, few riverine landscapes are unaffected by human stressors, which can result in changes to the physical structure, biotic population demography, biodiversity, plant and animal community structure, and food webs of these important freshwater ecosystems. However, rivers are also naturally dynamic ecosystems, thus separating the effects of natural and human-induced changes is often difficult, yet understanding the drivers of change is important for the rehabilitation/restoration of these complex adaptive systems.

Anthropocene Rivers are proposed to be structurally and functionally different from their "natural" cousins and in most cases cannot return to their previous state (Thoms and Fuller, 2024). Consequently, contemporary river management practices, such as efforts to restore near-natural flow regimes (i.e., environmental flows), levee removal, and the reintroduction of large wood to increase habitat availability, may not be well suited to these novel ecosystems. Relationships between humans and river ecosystems have also changed over time. The traditional command-and-control river management practices are being challenged by the recognition that rivers are social-ecological systems. Changes to the way rivers are perceived and framed have important implications not only for the management of riverine landscapes but also for how to model these landscapes, whether empirically or conceptually (Allan et al., 2024).

Managing rivers in the Anthropocene presents new challenges. The bewildering array of concepts and narratives, and the myriad of strategies that guide the practical application of river management activities contribute to this. Can river ecosystems be "restored" to some

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TABLE 1 Drivers of change, legacies, and social issues informing management of river ecosystems in the Anthropocene.

Driver	Activity	Process
Intensive land use and urbanisation	Agriculture	Intensive agriculture alters river flow through water extraction and pollution from pesticides and fertilizers, leading to eutrophication and loss of freshwater biodiversity
	Industry	Heavy industry along rivers can contribute to significant contamination and sedimentation, making the recovery of river ecosystems challenging
	Urban expansion	Urban growth frequently encroaches upon, straightens, and/or modifies river channels and adjacent floodplains to accommodate infrastructure. Urban areas contribute to increased surface runoff, pollution, and altered hydrology, making natural restoration difficult
Flow regulation and water extraction	Dams and weirs	These structures, built for water storage, hydropower, navigation, and irrigation, alter natural flow regimes, sediment transport, water temperatures, and fish migration patterns
	Water extractions	Excessive water withdrawal for agriculture, industry, and domestic use reduces river flow, impacting aquatic habitats and making it difficult to achieve natural flow conditions necessary for restoration
	Hydropeaking	Results in rapid changes in water flow and temperature, destabilizing freshwater ecosystems
Water quality	Nutrient pollution	Runoff containing excess nitrogen and phosphorus from agriculture and urban areas leads to algal blooms, hypoxia, and loss of aquatic life
	Toxic contaminants	Heavy metals, pharmaceuticals, and microplastics pose long-term threats to riverine ecosystems, often requiring complex and costly remediation
	Sewer overflows	Untreated discharge of sewage into rivers during heavy rains
Climate change	Altered hydrological regimes	Changing precipitation patterns, more intense storms, and prolonged droughts disrupt natural river dynamics, making it challenging to establish stable restoration baselines
	Temperature changes	Warmer water temperatures can affect species composition and the timing of biological events, such as fish spawning, complicating restoration goals
	Flooding and erosion	Greater frequency and intensity of floods alter river morphology, which can influence restoration activities by causing erosion and habitat destruction
Fragmentation and connectivity	Barriers to migration	Dams, roads, and other infrastructure fragment rivers, isolating fish populations and disrupting nutrient and sediment flow
	Altered sediment movement	Reduced sediment flow below dams leads to riverbed erosion and habitat loss downstream
	Floodplain levees	The construction of floodplain levees reduces the active floodplain area and restricts the lateral movement of flood waters
Competing stakeholder interest	Economic vs. Environmental goals	River systems often serve multiple human uses—agriculture, industry, hydropower, and recreation. Conflicts between stakeholders can arise when restoration goals, such as increasing water flow or removing a dam, conflict with established economic activities
	Regulatory and Policy challenges	Policies governing water use, land use, and environmental protection are often fragmented, making coordinated restoration efforts difficult
Legacy Impacts and Historical Modifications	Centuries of alteration	Rivers and floodplains have been heavily modified for centuries for navigation, flood control, and urban development. Reversing these changes often requires significant investment that will restore to pre-disturbance conditions
	Contaminated sediments	Legacy pollutants embedded in river sediments pose a risk of secondary contamination when disturbed, complicating restoration efforts
Socioeconomic Constraints	Funding and Resources	River restoration is often expensive, requiring long-term commitment. Securing consistent funding and resources is a major impediment
	Community engagement	Restoration projects that do not involve local communities often face resistance, especially when they impact land use, property rights, or recreational activities
Invasive Species	Non-Native species	Invasive plants, fish, and other organisms can outcompete native species, alter habitat structure, and disrupt food webs, making it difficult to restore natural ecosystem balance
	Restoration vs. Invasion risk	Some restoration techniques, such as reintroducing water flow, may unintentionally create favourable conditions for invasive species
Realistic goal and expectations	Unstable baselines	In the Anthropocene, defining what a "restored" river should look like is complex due to ongoing climate change, land-use changes, and species shifts. Restoration targets need to be dynamic and adaptable to new realities
	Ecosystem novelty	Anthropocene rivers will not return to historical states, requiring managers to adopt novel approaches and realistic benchmarks for success

pre-disturbance state in the Anthropocene? Do the objectives of river management in the Anthropocene need to change? Improving the health and function of river ecosystems (the focus of river rehabilitation and repair) must acknowledge that full restoration may not always be possible due to irreversible changes in the broader landscape. The resilience of rivers as social-ecological systems acknowledges that river management involves compromises between ecological goals and human needs (Thoms and Fuller, 2024). Thus, a focus on building the ability of rivers to absorb, adapt, and transform to future disturbances so they can continue to provide valued ecosystem services would reduce the uncertainty of river management in the Anthropocene.

The objective of this Research Topic is to explore various challenges and questions about Anthropocene Rivers and their rehabilitation. Case studies from different geographic regions and ecosystem perspectives around the world present alternative experiences of rehabilitating Anthropocene Rivers. These manuscripts explore and unpack various biophysical and social framings of these experiences and identify priorities for further research and management.

2 Contributions to river rehabilitation in the Anthropocene

Articles in this Research Topic provide insights from three continents, and four themes emerge from the studies presented. First, a conceptual framework for "river repair" is outlined by Greene et al. Based on components of resilience thinking, landscape ecology, and river science, river repair does not attempt to return or restore a river to a pre-Anthropocene state, rather it focuses on enhancing the resilience capacities of river ecosystems (Thoms and Fuller, 2024). Further, the authors suggest that a river-restoration mindset introduces an unconscious bias that can favor certain approaches and strategies that are often ineffective and unsuitable for managing river ecosystems in the Anthropocene.

Second, the benefits of including unregulated tributaries in river-repair strategies for larger regulated systems are discussed by Bouska et al. and Popp et al. River tributaries are often less altered, and offer fewer geopolitical constraints for repair, than those larger rivers into which they flow. Three case studies show the potential biological benefits of relatively "natural" tributaries to regulated mainstem rivers. The review by Bouska et al. which compares problems and solutions in the Missouri and Colorado rivers (USA), highlights four portfolio assets that tributaries provide to large-river fish populations in mainstem channels: 1) habitat diversity, 2) connectivity, 3) ecological asynchrony, and 4) density-dependent processes. Although the specific management actions may vary between river systems, the lessons learned can be used to guide river repair activities globally. The study presented by Popp et al. explores habitat use by common barbel (*Barbus barbus*) in the Wien River (Austria), a tributary of the Danube River. Through a series of translocation experiments it was shown that the Wien River offers potential spawning and nursery habitat to barbel populations in the main channel of the Danube River.

Third, the importance of managing altered sediment regimes is the focus of the studies presented by Fuller et al. and Wilke et al. Fuller et al. use geomorphic river stories from five rivers in New Zealand to show that targeted, fit-for-purpose, process-based rehabilitation programs are needed to address human-intensified disturbance in these systems. They provide examples of sediment-driven problems from the five rivers studied, which vary in geomorphology, and thus require specific, individual management plans to rehabilitate (or repair, *sensu* Greene et al.), though the lessons they share can be applied anywhere. Continuing with the problem of anthropogenically increased sedimentation, Wilke et al. present a step-by-step guide for repairing oxbows (also known as billabongs in Australia), in first-, second-, and third-order streams. They draw on 20 years of experience and lessons learned implementing oxbow repair in the midwestern USA, where human activities have degraded oxbows, which are an important part of river ecosystems. Although these two articles are from different geographic regions and address problems at different scales, both describe practical and effective programs for repairing essential parts and habitats of river ecosystems, thereby increasing their capacity to adapt under future disturbance regimes.

Fourth, issues of water management in the Anthropocene are presented by Perry et al., and Adams et al. In the Colorado River basin, water allocations are over-appropriated, and future climate change is projected to exacerbate groundwater scarcity. Perry et al. suggests that the current fragmented, scope-limited governance does not protect groundwater resources in the Colorado River basin, and this threatens a key contribution to baseflow in this river. The authors suggest an interstate groundwater compact is possible and provide examples like Tribal water rights and the Ogallala Aquifer Initiative, an agreement between eight states supported by federal aid. Anthropogenically increased stream temperature can negatively affect fish biology, and Adams et al. demonstrate that urban wastewater treatment plant effluent during wintertime is a key problem in cold-water streams. They studied the influence of air temperature, discharge, effluent temperature, and distance downstream on winter stream temperature, and found that effluent can warm winter stream temperature by as much as 12°C, an increase shown to affect the timing of fish reproduction. Moreover, this study showed that predicted changes in air temperature due to climate warming will have only slight effects on winter stream water temperature increases in this region, emphasizing the importance of addressing effluent discharge. Together, these articles show that unless conscientious planning is undertaken to protect important groundwater and surface water resources, humans and other biota that depend on these hydrologically connected systems could be at risk.

3 Future challenges for rehabilitating rivers in the Anthropocene

This Research Topic highlights several important challenges for river management in the Anthropocene. It is acknowledged that river management is a prominent area of theoretical and applied river science, which supports a multi-billion-dollar industry across many countries. The literature is replete with strategies and approaches to guide management activities focused on enhancing river ecosystem processes, form, and ultimately river health. A continuum of river management practices has emerged that attempts to reduce societal effects on rivers, from rehabilitating river ecosystems and initiating the "natural" recovery of rivers, to the full recovery of "natural" river ecosystem form and function. Despite the effort to ground these practices in scientific knowledge about river processes, the application and relevance of accepted paradigms that underpin river management are questionable in the Anthropocene. There is increasing evidence that most Anthropocene Rivers are "novel" ecosystems, and their responses to traditional river management activities can be unexpected, and typically they cannot be restored back to pre-disturbance states. Thus, establishing management targets for Anthropocene Rivers should not be solely based on restoring the structure and functions of pristine rivers as reference systems, but on the goal of resilient socially and biophysically valued ecosystems.

Understanding and predicting the response of Anthropocene Rivers to management activities is a challenge, and research in this area has been limited. Establishing the "state" and "behaviour" of Anthropocene Rivers is essential for the study and management of contemporary river ecosystems. River management activities represent a form of disturbance, and unpacking the response of Anthropocene Rivers to multiple human-induced disturbances and their interactions with natural disturbances is an essential future research area.

Rivers and people are tightly coupled, especially in the Anthropocene. How society and individuals relate to rivers dictates their understanding of rivers and approaches to river management. Viewing rivers as social-ecological systems requires knowledge of how social and ecological components interact to influence the ecosystems of these highly coupled systems. It also challenges the dominant view of river equilibrium, because that view is incompatible with the complex dynamics of social-ecological systems (Thoms and Fuller, 2024). Contemporary river management focuses mainly on biophysical processes, yet there must be an increased emphasis on understanding and incorporating the social, economic, and political domains of river management. Thus, a mindset change that seeks to understand the variability, heterogeneity, and complexity of ecological systems in their social and governance context will advance the management of rivers as social–ecological systems in the Anthropocene.

Since we cannot turn back time in the Anthropocene, navigating future uncertainties requires a paradigm shift for managing rivers. Focusing on enhancing the capacity of rivers to absorb, adapt, and transform in response to future disturbance regimes would foster strategic river management that promotes resilient river futures.

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