Governing transboundary river barriers: adaptive management challenges in South and Southeast Asia

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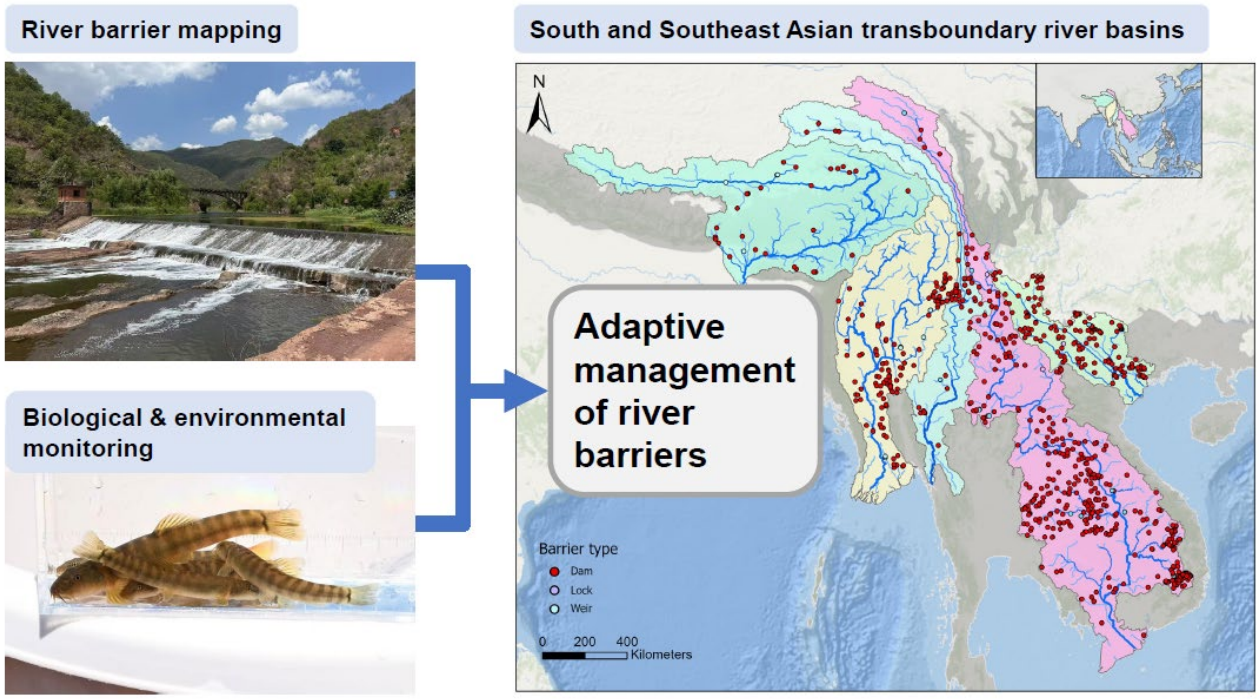
Graphical Abstract



Mapping river barriers and monitoring freshwater biodiversity are essential for adaptive basin management in South and Southeast Asia. It highlights the urgent need for complete, accessible databases to guide conservation and governance in transboundary river basins.

Abstract

Burgeoning expansion of anthropogenic river barriers in South and Southeast Asian transboundary river basins has led to the loss of natural flow regimes, fragmented river habitat, and altered environmental conditions to the detriment of native biodiversity and vital fisheries. Despite the increasing recognition of these threats, effective conservation planning and sustainable water management continues to be challenged by incomplete barrier databases and inconsistent biological monitoring programs. Here, we explore how comprehensive, harmonized, and openly accessible barrier databases, combined with systematic long-term biological and environmental monitoring programs, are essential to accurately assess river connectivity and guide collaborative conservation

strategies. We illustrate a mechanism by which this can be achieved through an adaptive management framework applied to the Lancang-Mekong Basin, and offer broader lessons related to long-standing policy and water governance challenges facing transboundary river basins in a changing world.

Introduction

The impacts of anthropogenic barriers (e.g., dam, weir, sluice gate, culvert) on river ecosystems are widely recognized (Vörösmarty et al. 2010, Reid et al. 2019, He et al. 2024, Keijzer et al. 2024), particularly for large, biodiverse river basins, where many freshwater species face a growing risk of extinction due to habitat fragmentation and flow alteration (Winemiller et al. 2016, Flecker et al. 2022, Cooke et al. 2024). It is estimated that river barriers are a primary cause of decline in close to half (45%) of threatened freshwater fish megafauna (Carrizo et al. 2017), as well as for numerous other freshwater species (He et al. 2024). More broadly, river barriers threaten global commitments to conserving habitat connectivity, a key target of the Kunming-Montreal Global Biodiversity Framework (GBF) aimed at halting human-induced species extinctions and sustaining biodiversity by 2050 (United Nations Convention on Biological Diversity 2022).

Transboundary Asian rivers and the challenges of physical barriers

Five major transboundary river basins (i.e., Yarlung Tsangpo-Brahmaputra, Dulong-Irrawaddy, Nu-Salween, Lancang-Mekong, and Yuan-Red) lie within the Indo-Burma, Himalaya, and Mountains of Southwest China biodiversity hotspots in South and Southeast Asia (Figure 1). These basins are characterized by distinct landforms and a wide diversity of ecosystems, making them critical conservation areas. Flagship species such as Mekong giant catfish *Pangasianodon giga*s, giant carp *Catlocarpio siamensis* and gharial *Gavialis gangeticus* are all critically endangered megafauna of this region, and require large areas of relatively

unmodified habitats for population persistence (Carrizo et al. 2017, Lynch et al. 2023). Maintaining functioning and well-connected habitats is well recognized as being crucial for the conservation of these species (Carrizo et al. 2017, He et al. 2018, 2019).

Transboundary rivers of South and Southeast Asia flow through several countries with contrasting political systems, economic interests, and water governance systems (Rogers et al. 2023). Historically, riparian countries prioritized exploiting their portion of the basin's water resources potential to meet domestic energy and irrigation needs, and export electricity to neighboring countries, without accounting for the trade-offs between immediate benefits and the cumulative impacts of barriers at the basin scale (Wei et al. 2022, Li et al. 2025). The rapid expansion of river infrastructure development since the 1990s, has generated vigorous debate over the impacts of river barriers on ecosystem services such as fisheries production and on biodiversity (Hecht et al. 2019, Intralawan et al. 2019, Sun et al. 2023). However, difficulties in detecting the location of small barriers (e.g., small dams, weirs, sluice gates) has led to incomplete open-access barrier databases (Baumgartner et al. 2022, Rogers et al. 2023, Sun et al. 2024), contributing to an inaccurate picture of habitat connectivity (Figure 1). This is despite the major impacts that numerous small barriers have on river habitats and biodiversity (Silva et al. 2017; Belletti et al. 2020; Morden et al. 2020). Existing open-access databases captured less than 3% of the total barriers now identified in the Mekong Basin, highlighting the severe underestimation of barrier presence and the urgent need for more comprehensive mapping efforts (Sun et al. 2024). The accuracy of river fragmentation status is paramount to quantify the ecological impacts of dams (Morden et al. 2022, Rogers et al. 2023), inform the prioritization of dam removal and mitigation efforts (Jumani et al. 2023), and more broadly promote and guide ecologically sustainable river management. In complete dam databases challenge efforts to meet the GBF’s target to maintain and restore ecosystem

integrity, resilience, and connectivity (United Nations Convention on Biological Diversity 2022). To promote sustainable river management, an adaptive management plan for river barriers is urgently needed in these basins.

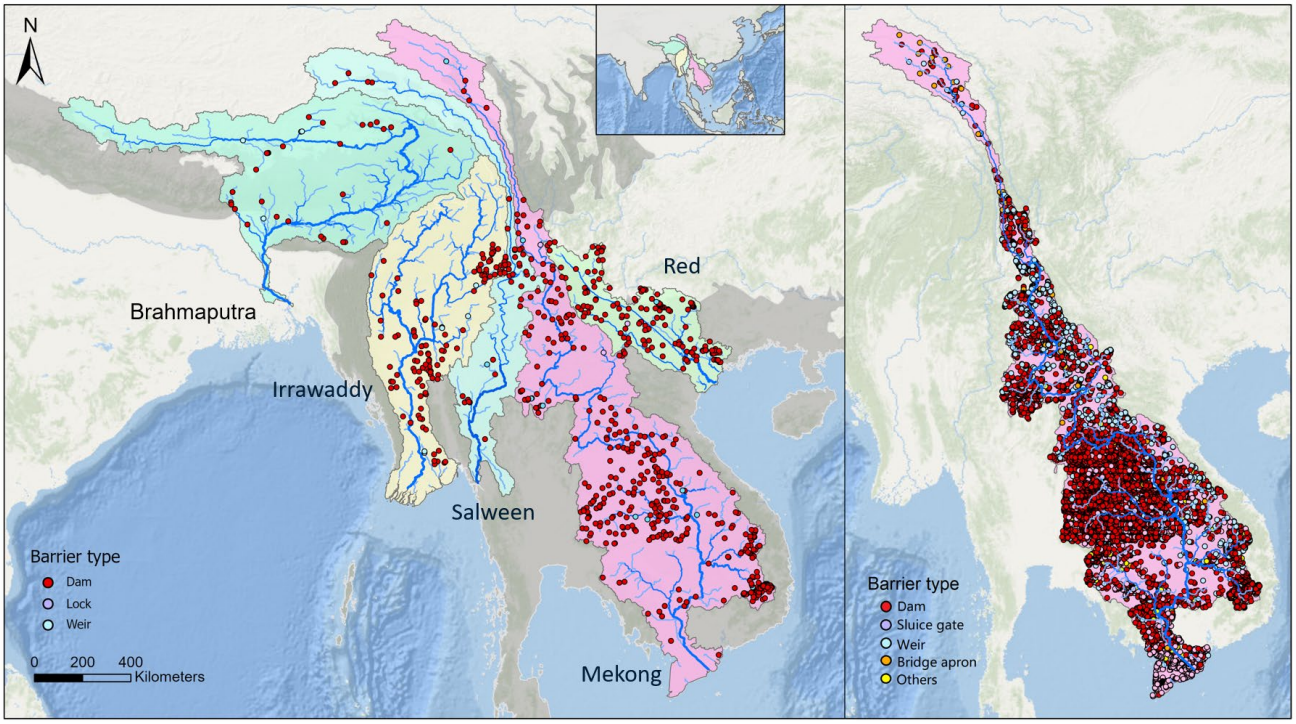


Figure 1. Locations of five major transboundary basins (colour shading) within the biodiversity hotspots (grey shaded area) in South/South-East Asia. The left panel highlights the river barriers from the Global Dam Watch database (https://www.globaldamwatch.org/database). In comparison, the right panel showcases barriers in the Lancang-Mekong Basin, recorded in the Mekong River Barrier Database (https://zenodo.org/records/10141668).

Challenges of Managing Barriers in Transboundary Asian Rivers

In Europe, the environmental objectives of the Water Framework Directive (WFD; 2000/60/EC) provide a strong driver for restoring river continuity and achieving good ecological status (Smith et al. 2014). To achieve the

WFD's objectives, the Adaptive Management of Barriers in European Rivers (AMBER) project systematically applies adaptive management strategies (Birnie-Gauvin et al. 2017), effectively restoring river connectivity through informed barrier operation and management (Belletti et al. 2020). The AMBER project, benefiting from systematic barrier and river biota surveys, stable political conditions and robust environmental legislation, has compiled a comprehensive open-access barrier database of approximately 630,000 unique river barriers, facilitating targeted restoration projects across 36 European countries (Belletti et al. 2020).

Unlike Europe's unified regulatory approach under frameworks like the WFD, Asia's transboundary river basins are characterized by diverse governance systems, geopolitical tensions, varying economic priorities, and insufficient systematic environmental monitoring programs (Sahana et al. 2024). Data sharing is a long-standing obstacle for these transboundary basins, which has hampered the ability of riparian countries to sustainably manage water resources and conserve aquatic biota across the basin scale (Gao et al. 2022, Lin et al. 2023). Currently, several cooperation mechanisms have been established for the Lancang-Mekong basin, such as the Mekong River Commission, Greater Mekong Subregion, and Lancang-Mekong Cooperation. These mechanisms have contributed to a certain level of information exchange regarding river infrastructure and fish data between riparian countries, but no such mechanisms exist for the remaining basins. Even where such agreements acknowledge that river health is important, implementation is hampered by a lack of coherent monitoring efforts and inadequate indicators for tracking trends over time and guiding investments in river management (Kuehne et al. 2023).

In addition to geopolitical complexities, incomplete barrier surveys and the absence of systematic, long-term biological monitoring programs severely limit the understanding of river fragmentation impacts and the

effectiveness of conservation efforts within South and South-East Asian transboundary rivers, but more widely also (Maasri et al. 2022, Ioannidou et al. 2023). Current basin-scale barrier databases primarily document larger barriers, overlooking smaller structures that significantly impact ecological connectivity (Sun et al. 2024, 2025). Moreover, socio-economic factors pose additional complexities (Anderson et al. 2019). Many communities in South and Southeast Asia depend heavily on rivers for livelihoods and daily subsistence (Kang and Huang 2021, Galib et al. 2023, Lynch et al. 2023), potentially resisting conservation initiatives perceived as limiting traditional resource use (Winemiller et al. 2016, Galib et al. 2023). Thus, successful implementation of adaptive management approaches in the context of Asian transboundary basins must tackle these governance, socio-economic, and data-collection challenges. Strategic planning that integrates systematic long-term biological monitoring, inclusive data-sharing agreements, and harmonized, openly accessible barrier databases can substantially improve conservation outcomes and enhance collaborative water management among riparian countries (Maasri et al. 2022).

Deep learning facilitates database creation, but more data sources are needed

Technological advances, such as deep learning technology, has recently enabled the development of a comprehensive open-access river barrier database for the Mekong Basin (Sun et al. 2024), identifying over 13,000 barriers, including dams, weirs, and sluice gates. This represents a significant advancement compared to the existing global databases, such as the Global Dam Watch inventory, which currently lists only 427 major barriers in the region (Lehner et al. 2024). Despite this progress, important barrier characteristics (e.g., height, slope, hydropower capacity) remain largely unavailable, highlighting the need for further stakeholder contributions to enhance database completeness and practical utility for basin management.

Providing openly accessible barrier data enables stakeholders including researchers, conservationists, and policymakers to better understand and mitigate the ecological impacts of river barriers. It facilitates sustainable management practices by identifying priority areas for restoration actions (Garcia de Leaniz and O'Hanley 2022), such as fish pass installation or barrier removal, thereby improving habitat connectivity crucial for threatened aquatic biodiversity (Silva et al. 2018, Belletti et al. 2020, Sun et al. 2025). Currently, the Mekong River Barrier Database is unique in its completeness among Southeast Asian transboundary basins, underscoring the importance of expanding such efforts to other regions.

Opportunities for adaptive management of river barriers in Asia

To achieve sustainable management of transboundary rivers within the target basins, developing comprehensive, open-access barrier databases combined with systematic, long-term biological and water monitoring programs is essential. This should include a comprehensive set of scalable indicators that can support "top-down" global surveillance while also facilitating standardized "bottom-up" local monitoring efforts (Kuehne et al. 2023). Included among these programs, is a robust stream flow gauging network, and associated open-access databases, that are representative of socioecological, hydrologic, climatic, and physiographic diversity of rivers in Asia (Krabbenhoft et al. 2022). Utilizing advanced technologies, including GIS mapping, machine learning and deep learning, can greatly facilitate comprehensive and accurate mapping of river barriers across extensive and remote areas (Sun et al. 2025).

Regional cooperation is vital to overcome existing data-sharing barriers and geopolitical complexities (Gao et al. 2022, Eckert et al. 2023). For example, transboundary research consortia can be created with universities and research institutes to maintain long-term monitoring programs. Local stakeholders including fishers,

farmers, and community groups can be trained and incentivized to participate in collection of biological samples (including eDNA monitoring) and river barrier data (Stoffers et al. 2024), to enhance database accuracy (Belletti et al. 2020). Biological monitoring should be conducted at key barrier construction sites to track impacts and inform adaptive management strategies.

Furthermore, harmonizing governance frameworks through international agreements such as the UN Water Convention can improve coordination among riparian countries, promoting shared responsibility and trust-building (Eckert et al. 2023). Securing financial and technical support from international organizations (e.g., The Nature Conservancy, World Resources Institute) can further support database development, maintenance, and capacity building.

Together, these measures provide an essential foundation for informed decision-making, balancing multiple demands for water use while preserving ecological integrity. Effective adaptive management can thus help allocate water resources sustainably, reconciling socio-economic development with conservation objectives critical for biodiversity preservation and the long-term ecological health of transboundary river basins.

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Conflict of Interest

Authors declare that they have no competing interests.

Authors contribution

JS and MCL contributed to the conceptualization and discussion of the content. JS led the writing and all authors (JS, MCL, JO, and DH) contributed substantially to the drafts of the manuscript. All authors reviewed and edited the manuscript before submission.