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REVIEW ARTICLE

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Integrating waters, bridging boundaries: a comprehensive review of Transboundary Mega-Basin Management for sustainable and equitable water governance

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ABSTRACT

This review explores the significance of transboundary mega-basin management (TMBM) in promoting sustainable and equitable governance of shared water resources. In the context of increasing water demand and climate variability, we assess how TMBM, which builds on integrated water resource management (IWRM) principles, addresses complex governance challenges. By analysing global case studies, including the Nile, Colorado, Mekong and Senegal River basins, we highlight effective practices in collaboration, benefit-sharing and adaptive governance. This study contributes to the conversation on global water governance by advocating innovative and inclusive strategies that ensure water security, environmental sustainability and peaceful international relations.

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Introduction

Water is fundamental for life, human development and ecosystem integrity. However, managing water resources is becoming increasingly complex, especially when rivers, lakes and aquifers cross national borders. Over 60% of the world's freshwater flows through transboundary basins that are shared by two or more countries (Uitto & Duda, 2002). Global pressures from climate change, rapid population growth, industrial development and urbanization have intensified the urgent need for cooperative transboundary water management (Akamani & Wilson, 2011). Nations that share water resources must navigate political, economic and environmental tensions to ensure sustainable and equitable access to water. Without effective governance mechanisms, competition over scarce water resources can exacerbate existing conflicts and threaten regional stability (Carter & Parker, 2009).

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Transboundary water management (TWM) has traditionally focused on negotiating water-sharing agreements between states. These frameworks often emphasize sovereignty and the allocation of water quantities, sometimes at the expense of broader issues, such as environmental sustainability, adaptive capacity and benefit-sharing opportunities (Earle & Bazilli, 2013; Mylopoulos & Kolokytha, 2008). Moreover, many existing treaties and institutions lack the flexibility required to respond to evolving challenges, including climate-induced hydrological variability and shifts in demographic and economic pressure (Timmerman & Langaas, 2005). Recognizing the limitations of conventional TWM approaches, scholars and practitioners have called for more integrative, adaptive and inclusive models of transboundary water governance.

One such emerging concept is transboundary mega-basin management (TMBM). TMBM refers to the governance of large-scale river basins that involve multiple riparian countries and exhibit complex socio-ecological interactions across vast geographies (Wang et al., 2025). These mega-basins, such as the Nile, Amazon, Mekong and Colorado River basins, present unique governance challenges due to their ecological diversity, varied stakeholder interests and political sensitivities. TMBM builds on the principles of integrated water resource management (IWRM), which advocates the coordinated development and management of water, land, and related resources to maximize economic and social welfare without compromising the sustainability of vital ecosystems (Giordano & Shah, 2017; Keur et al., 2008).

However, TMBM extends beyond IWRM by addressing the needs of large transboundary systems. While IWRM emphasizes integration at multiple scales, TMBM specifically confronts the complexities of governing vast hydrological units, where cross-sectoral coordination, climate adaptation and equitable benefit sharing must be achieved across diverse political and institutional contexts. Unlike traditional frameworks that focus narrowly on water quantity allocation, TMBM promotes holistic management that integrates considerations of climate resilience, socioeconomic equity, ecological sustainability and cultural values (Deribe et al., 2024; Porcher & Saussier, 2019).

The need for an evolved framework, such as TMBM, is underscored by the increasing frequency and intensity of extreme climate events. Floods, droughts and altered hydrological cycles place unprecedented pressures on shared water systems, amplifying vulnerabilities and deepening inequalities among riparian states (Adhikari et al., 2015; Frappart, 2020). Managing such complexities requires flexible, adaptive and participatory governance mechanisms that can transcend the traditional state-centric models. Benefit-sharing frameworks, ecosystem-based management and multi-stakeholder engagement are key elements of effective TMBM strategies (Sadoff & Grey, 2002; Rivera-Torres & Gerlak, 2021a).

Moreover, the TMBM explicitly acknowledges the interplay between environmental constraints and socioeconomic needs. Achieving equitable water governance is not merely about dividing water flows but also ensuring that all basin states and communities derive tangible and intangible benefits, including food security, energy access, flood protection, biodiversity conservation and cultural preservation (Chen et al., 2015). The Senegal River basin is a prime example of effective transboundary water governance, mainly due to the cooperative management model used by the Organization pour la Mise en Valeur du fleuve Sénégal (OMVS, 2016). This initiative is considered successful because it has established

fair benefit-sharing among member states, ensuring that economic, social and environmental benefits from shared water infrastructure are shared equitably. Through joint ownership of major projects, inclusive decision-making and strong legal frameworks, OMVS has promoted continuous regional growth, improved environmental care and maintained political stability. The organization's dedication to stakeholder involvement and adaptable governance further boosts its ability to tackle new challenges, making it a model for other transboundary basins aiming to balance development with sustainability and cooperation (Biswas & Tortajada, 2016).

Despite notable success, the operationalization of TMBM remains challenging. Political asymmetries between upstream and downstream countries, competing national interests, institutional fragmentation and limited financial resources can hinder effective collaboration (Zeitoun & Mirumachi, 2008). Legal agreements must be adaptable and inclusive considering the dynamic nature of water availability, environmental degradation, demographic shifts and changing geopolitical realities. Furthermore, stakeholder engagement must extend beyond government actors to include local communities, indigenous groups, private sector participants and non-governmental organizations (Nasr & Neef, 2016; Wolf, 1998).

Given these complexities, this review addresses the following key research question: How can TMBM frameworks build integrated water resource management (IWRM) principles and enhance sustainability, equity and cooperative governance in managing large-scale transboundary water resources?

To address this question, this review critically analyses the legal, institutional and policy frameworks that underpin TMBM; evaluates how principles of sustainability and equity are embedded within existing governance arrangements; and explores the role of stakeholder participation in promoting collaborative outcomes. The study draws upon case studies from major transboundary basins, including the Nile, Colorado, Mekong and Senegal Rivers, to illustrate the successes, challenges and lessons learned. By synthesizing theoretical insights and empirical experience, this review aims to offer practical recommendations for advancing transboundary water cooperation in an era of intensifying environmental and societal pressures. Effective management of transboundary mega-basins ultimately requires moving beyond fragmented sectoral approaches towards integrated, cooperative and adaptive strategies that reflect the complex realities of shared water governance. Advancing TMBM principles will promote sustainable development, ensure water security, enhance environmental resilience and foster peaceful international relations in the 21st century.

To comprehensively address the research question and critically explore the potential of TMBM frameworks, this study adopted a thorough review methodology. Rather than strictly adhering to systematic review protocols, the approach prioritizes both breadth and depth by integrating insights from peer-reviewed literature, policy documents, grey literature and key international case studies (Stratton, 2016). The following section outlines the strategies used to search, select and analyse relevant sources, ensuring a holistic synthesis of theoretical perspectives, governance practices and empirical experiences across different transboundary water basins.

Methodology

Study design

This study adopts a comprehensive review methodology to address the research question. This method enables a richer understanding of the diverse legal, institutional and governance frameworks that underpin TMBM (Deribe et al., ; Varady et al., 2023). Comprehensive reviews are especially suited for emerging interdisciplinary topics where strict systematic procedures may limit contextual insights (Pahl-Wostl et al., 2023).

Search strategy

A literature search was conducted between January and March 2024, using multiple academic databases and search engines. The databases used included Web of Science, Scopus and ScienceDirect, while Google Scholar and general Google searches were employed to locate grey literature and reports from reputable organizations such as UN-Water, the World Bank and the Global Water Partnership (GWP). The search strategy employed specific key phrases to capture the breadth of literature relevant to the research focus. These included terms such as '*transboundary water management*', '*transboundary mega-basin governance*', '*integrated water resources management (IWRM)*', '*climate resilience in water governance*', '*benefit-sharing in river basins*', '*stakeholder participation in transboundary water governance*', and '*adaptive governance in international river basins*'. These search phrases were systematically applied across academic databases and/or supplemented by Boolean operators (AND and OR) to ensure a comprehensive and inclusive collection of sources reflecting the core dimensions of transboundary mega-basin management.

Screening and selection process

The initial database search generated approximately 2045 records. After removing duplicates, 1430 documents were screened for relevance based on titles and abstracts. The screening criteria focused on identifying studies addressing transboundary water governance, sustainability, stakeholder engagement, benefit-sharing frameworks and climate resilience within large-scale international basins.

A total of 290 documents underwent full-text review, with inclusion criteria requiring each document to focus on transboundary or international water governance, discuss legal, institutional or stakeholder participation frameworks, address sustainability or equity issues, be published between 1995 and 2024, and be available in English.

Studies were excluded if they focused solely on domestic (single country) water management, including only hydrological or engineering analyses with no relevance to governance, or if the full text was unavailable. As a result, a final dataset of 108 peer-reviewed articles and 24 grey literature sources were selected for detailed thematic analysis.

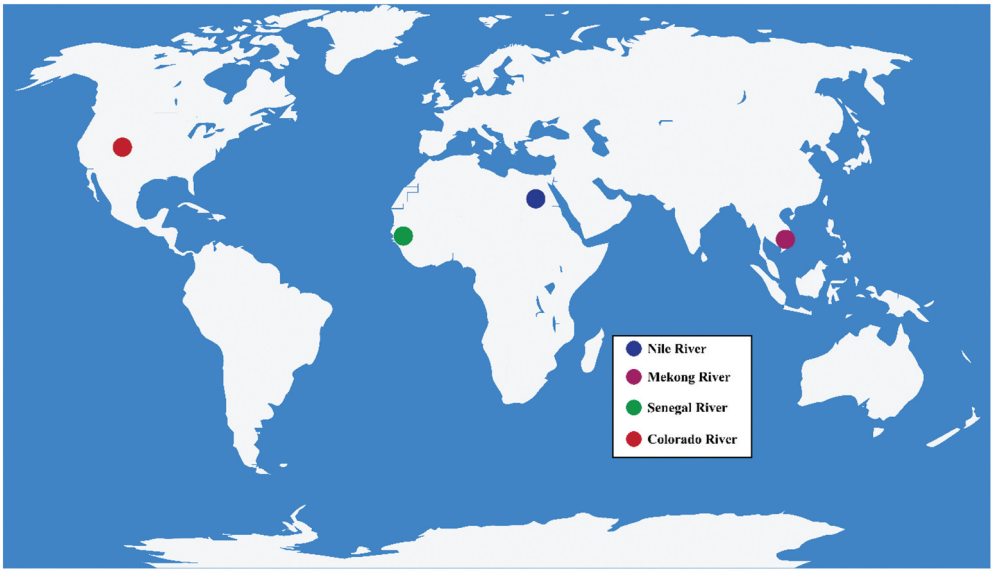

Figure 1. Geographic distribution of major transboundary river basins analysed in this review.

Case study selection criteria

To enrich the comprehensive literature review, selected case studies were drawn from major transboundary river basins based on four key criteria: geographic diversity, scale and complexity, data availability and relevance to TMBM principles (Figure 1). The selection ensured representation from Africa, North America, Asia and South America, with a focus on basins characterized by multiple riparian states, notable governance challenges and existing cooperative frameworks. Only cases with sufficient peer-reviewed or institutional documentation were considered. Additionally, the chosen basins exemplify critical aspects of TMBM, including benefit-sharing mechanisms, climate adaptation strategies, stakeholder participation and institutional innovations. Accordingly, the Nile River basin, Colorado River basin, Mekong River basin and Senegal River basin were included as illustrative examples (Biswas & Tortajada, 2016; Deribe et al., ; Rivera-Torres & Gerlak, 2021b).

Analytical approach

The analysis used a thematic synthesis approach as described by Thomas and Harden (2008). After a thorough reading and coding of the selected literature and case studies, five main themes were identified: legal and institutional arrangements, stakeholder engagement processes, benefit-sharing strategies, integration of climate resilience into governance structures and adaptive governance innovations. A comparative perspective was then employed across the chosen transboundary river basins to identify shared challenges, emerging innovations and location-specific governance practices. This cross-regional synthesis allowed for the

extraction of broader insights relevant to the governance of transboundary mega-basins worldwide, improving the applicability of the findings beyond the cases studied (Cheverud et al., 1989; Gulshad et al., 2024).

Limitations

This review was limited to studies published in English, which may have excluded relevant studies available in other languages. While grey literature was included to complement peer-reviewed sources, only publicly accessible and reputable reports were considered to ensure the credibility and reliability of the findings. Given the broad scope of TMBM, some case studies may have been covered in greater detail than others depending on the availability and depth of documented information. Furthermore, although it would have been beneficial to incorporate literature published in 2025, the search was restricted to studies published between 1995 and 2024, as the manuscript preparation and submission took place in 2024. Nonetheless, a comprehensive review approach was deemed appropriate for capturing the complexity and diversity of evolving TMBM practices (Varady et al., 2023).

Results

Legal and institutional frameworks for TMBM

This review highlights that robust legal and institutional frameworks are foundational to effective TMBM. Most transboundary governance initiatives have evolved from historical treaties, which often emphasize water quantity allocation without fully addressing broader sustainability or equity concerns. However, recent developments have gradually integrated adaptive management with ecosystem-based approaches. For instance, the Nile Basin Initiative (NBI), established in 1999, represents a shift towards a more inclusive, cooperative platform among Nile riparian countries, focusing not only on equitable water allocation, but also on joint socioeconomic development and environmental sustainability (Deribe et al., ; Swain, 2011). Similarly, the Colorado River basin governance structure evolved from the Colorado River Compact of 1922 to more recent binational agreements, such as Minute 319 and Minute 323, which embed adaptive management principles and climate resilience considerations (Rivera-Torres and Gerlak, 2021a).

In the Mekong basin, the Mekong River Commission (MRC) provides a formal legal and institutional mechanism for cooperation among Lower Mekong countries (Lee & Lee, 2015). Although the MRC does not have enforcement powers, its Procedures for Notification, Prior Consultation, and Agreement (PNPCA) framework fosters negotiation and dispute resolution among its members (Ratner, 2003). The Senegal River basin's OMVS is often cited as a best-practice example of joint legal and institutional management, emphasizing equitable benefit-sharing among member states (Biswas & Tortajada, 2016). Overall, the results indicate that while all studied basins have established some form of cooperative governance, the degree to which legal frameworks incorporate sustainability, adaptive governance and inclusivity varies significantly across cases.

Stakeholder participation and inclusivity

Stakeholder engagement has been increasingly recognized as a critical dimension of TMBM frameworks. The analysis shows that institutional mechanisms that allow diverse stakeholders to participate, including local communities, the private sector and civil society, can substantially enhance cooperation and compliance. The OMVS in the Senegal River basin stands out for embedding stakeholder engagement into its decision-making processes, involving not only governments, but also water users, local authorities and development partners (Faye, 2023). This inclusive model has contributed to sustained cooperation and equitable resource distribution in Senegal, Mali, Mauritania and Guinea. In the Colorado River basin, the engagement of municipal users, Native American tribes, agricultural users and environmental groups has become more formalized over the past two decades, particularly during negotiations leading to Minute 319 and Minute 323 (Sanchez and Cortez-Lara, 2015). This broader participation has led to more flexible and adaptive agreements that address diverse water needs.

Conversely, stakeholder participation in the Nile basin has remained limited. Although the Nile Basin Initiative promotes regional dialogue among states, direct engagement with non-state actors and local communities remains sporadic (Cascão, 2009; Swain, 2011). In the Mekong basin, while the MRC holds consultations with affected communities during major infrastructure projects, criticisms persist regarding the quality and influence of these consultations (Cronin & Hamlin, 2010). These results suggest that meaningful stakeholder participation remains unevenly embedded across TMBM frameworks, affecting the legitimacy, transparency and adaptability of transboundary governance.

Benefit-sharing mechanisms

Beyond traditional water quantity allocation, benefit-sharing mechanisms represent a major evolution in TMBM. The results demonstrate that successful transboundary mega-basin management increasingly involves equitable sharing of multiple benefits, including hydropower generation, irrigation, food security, environmental protection and regional development. The Senegal River basin provides a leading example in which shared infrastructure projects, such as the Manantali Dam, distribute electricity among member states, creating direct economic and social benefits beyond simple water use (Biswas & Tortajada, 2016; Faye, 2023). This arrangement strengthened interstate cooperation and helped reduce potential tension. In the Colorado River basin, binational collaboration between the United States and Mexico, particularly under Minutes 319 and 323, has expanded to include environmental restoration projects, such as pulse flows, to rejuvenate the Colorado River delta, illustrating an evolution from water quantity allocation to environmental benefit-sharing (Rivera-Torres and Gerlak, 2021b).

The concept of benefit-sharing in the Mekong basin has been officially acknowledged under the 1995 Mekong Agreement; however, its practical implementation has been limited. Controversies surrounding hydropower development, particularly mainstream dam construction in Laos and Cambodia, highlight the ongoing challenges in ensuring equitable benefit-sharing among member states and affected communities (Ratner, 2003). The Nile Basin Initiative has promoted benefit-sharing narratives, emphasizing

joint socioeconomic projects; however, upstream-downstream tensions, particularly between Egypt, Sudan and Ethiopia, continue to limit the full realization of shared benefits (Deribe et al., ; Swain, 2011). Thus, while benefit-sharing principles are increasingly recognized across TMBM efforts, their operationalization remains highly context-dependent.

Integration of climate resilience into TMBM frameworks

Climate resilience has become an increasingly important consideration within TMBM frameworks; however, the results reveal significant variation in how different basins integrate climate risks into their governance structures. The Colorado River basin demonstrates proactive incorporation of climate change considerations. Agreements such as Minute 323 specifically address adaptive management under scenarios of reduced river flow, establishing mechanisms for shared shortage responses between the United States and Mexico (Rivera-Torres and Gerlak, 2021a). In the Mekong basin, the MRC initiated flood management and drought monitoring programmes, recognizing the growing impact of climate variability on water availability and food security (Phy et al., 2025). However, political disagreements and funding constraints have limited the integration of basin-wide climate adaptation strategies. Conversely, in the Nile Basin, although the Cooperative Framework Agreement (CFA) mentions climate change, there are limited concrete mechanisms within the NBI for basin-wide climate adaptation planning (Deribe et al., ; Swain, 2011). The reliance on unilateral adaptation projects such as the Grand Ethiopian Renaissance Dam (GERD) further complicates cooperative climate resilience efforts. The Senegal River basin shows a relatively advanced integration of climate risks through joint infrastructure planning and adaptive management protocols partially supported by international development agencies (Faye, 2023). Overall, although climate resilience is increasingly acknowledged in principle, its operational integration within TMBM frameworks remains inconsistent and frequently underdeveloped.

Challenges and barriers to effective TMBM

The findings highlight several persistent challenges that undermine the full realization of TMBM frameworks. These challenges include asymmetrical power relations between upstream and downstream states, financial limitations, institutional fragmentation, political mistrust and lack of enforcement mechanisms.

In the Nile basin, upstream-downstream tensions, particularly between Ethiopia and Egypt, remain a major barrier to cooperative management. The GERD project has reignited longstanding disputes over historical water rights and future water security (Cascão, 2009; Swain, 2011). The Mekong Basin faces significant challenges related to divergent national development priorities, especially concerning hydropower projects, which have strained relations between Lower Mekong countries and upstream non-MRC members, such as China (Cronin & Hamlin, 2010). In the Colorado River basin, despite considerable progress, issues of water scarcity, legal rigidity of the 1922 Compact and environmental degradation continue to pose significant governance challenges,

particularly during prolonged drought conditions (Rivera-Torres and Gerlak, 2021b). Even the Senegal River basin, often cited as a model, faces emerging pressures related to population growth, infrastructure maintenance and evolving climate risks, which test the resilience of cooperative structures (Faye, 2023). Thus, although significant advances in TMBM frameworks have been made, achieving sustainable, equitable and climate-resilient transboundary water governance remains a dynamic and contested issue.

Cross-cutting themes and general insights from the literature

In addition to the findings from the four primary case studies, the broader literature review revealed several recurring themes and conceptual advancements relevant to the practice and evolution of TMBM. These themes further address the research question by identifying critical success factors, structural limitations and evolving governance priorities across a broader set of transboundary basins.

First, the literature consistently emphasizes the importance of polycentric and nested governance systems in managing transboundary mega-basins. Instead of relying solely on centralized institutions, successful TMBM frameworks often involve multiple overlapping authorities that operate at different spatial and administrative scales (Pahl-Wostl et al., 2023). This structure can enhance flexibility and responsiveness to local needs, while maintaining regional coherence.

Second, data sharing and joint knowledge production are highlighted as enablers of trust and evidence-based decision making. Shared hydrological monitoring systems, regional data repositories and co-developed scenario models have enhanced transparency and legitimacy in Danube, Rhine and Orange-Senqu (De Stefano et al., 2010). However, such platforms remain absent or politically constrained in other contexts, including parts of the Nile and Ganges Brahmaputra basins (Zeitoun & Mirumachi, 2008).

Third, this review found that gender equity and social inclusion remain underdeveloped in many TMBM frameworks. While IWRM principles emphasize the importance of inclusive governance, a few basin organizations operationalize gender-sensitive strategies or ensure the participation of marginalized groups in decision-making processes (Sultana & Loftus, 2012). The limited integration of these dimensions undermines the long-term legitimacy and social sustainability.

Fourth, the literature points to the increasing role of international donors, financial institutions and multilateral organizations in shaping TMBM governance architecture. While this support often catalyses cooperation and institutional development, it can also lead to dependency or externally driven agendas that may not align with local priorities (Warner & Zawahri, 2012). Ensuring local ownership and long-term financial autonomy remain central challenges.

Finally, the review indicated that legal ambiguity still affects many transboundary basins. The vague treaty language, absence of enforcement mechanisms and reliance on non-binding memoranda hinder legal certainty and weaken accountability (Lautze et al., 2013). This situation is particularly problematic in conflict-prone basins, or where political asymmetries between states are pronounced. Together, these cross-cutting insights reinforce the idea that, while case-specific innovations are essential, broader

structural reforms and institutional learning are equally vital for advancing TMBM frameworks towards more sustainable, equitable and cooperative governance outcomes.

Discussion

Revisiting the research question

This review examines how TMBM frameworks, grounded in the principles of IWRM, can contribute to sustainability, equity and cooperative governance in managing large-scale, transboundary water systems. Thematic findings, supported by diverse case studies and cross-cutting insights, indicate that TMBM offers conceptual and practical advancements beyond conventional TWM approaches. However, these advancements have not been uniformly applied and remain constrained by institutional, political and capacity-related barriers.

Sustainability outcomes through integrated planning

The TMBM contributes to sustainability by embedding long-term ecological considerations into basin planning. Traditional TWM often prioritizes water quantity allocation based on political agreements without sufficient integration of environmental needs. By contrast, TMBM seeks to manage water, land and ecological systems as interconnected resources, promoting basin-scale ecosystem restoration, climate adaptation and adaptive governance (Pahl-Wostl et al., 2023). For instance, the environmental flows of the Colorado River delta under Minutes 319 and 323 illustrate a shift from mere allocation to restoring ecosystem services (Rivera-Torres and Gerlak, 2021b).

The joint hydropower development of the Senegal River basin also demonstrates how sustainability can be institutionalized through cooperative infrastructure and shared energy outcomes (Biswas & Tortajada, 2016). However, the Nile and Mekong basins reveal the challenges of implementing such approaches, where competing national interests override the ecological sustainability goals (Cronin & Hamlin, 2010; Swain, 2011).

Enhancing equity through benefit sharing

Traditional transboundary frameworks tend to focus on allocative equity, that is, who receives the amount of water. However, TMBM reframes equity through the lens of benefit-sharing, emphasizing access to a broad range of socioeconomic and environmental benefits (Sadoff & Grey, 2002). These may include hydropower, agriculture, flood control, navigation and even intangible benefits such as regional stability and trust-building. The OMVS model for the Senegal basin is exemplary in this regard. It has institutionalized the equitable sharing of both costs and benefits, leading to long-term cooperation and infrastructure co-ownership (Faye, 2023). In contrast, the Nile basin has made limited progress in this direction, as benefit-sharing rhetoric remains hindered by entrenched legal and political disputes (Cascão, 2009).

Advancing governance through stakeholder participation and institutional flexibility

The TMBM frameworks are also distinguished by their emphasis on multilevel stakeholder participation and flexible governance arrangements. Traditional TWM frameworks often operate through top-down intergovernmental negotiations, whereas TMBM seeks to create polycentric systems that incorporate local actors, civil societies and knowledge institutions (Ostrom, 2010; Pahl-Wostl et al., 2023). This inclusivity enhances the legitimacy and responsiveness of the governance structures. Case studies show varied progress: the Colorado and Senegal basins exhibit strong participatory models, while the Mekong and Nile basins struggle with uneven or symbolic stakeholder engagement (Cronin & Hamlin, 2010; Sanchez and Cortez-Lara, 2015).

How TMBM differs from traditional transboundary water management

A key contribution of this review is that it clarifies the conceptual and operational distinctions between TMBM and traditional TWM. While TWM focuses on bilateral or multilateral agreements, primarily concerning water allocation and conflict avoidance, TMBM represents an expanded paradigm that incorporates integrated, adaptive and multi-scalar governance approaches. The five key differences identified in the literature are as follows.

Scale and complexity. Traditional TWM often applies to relatively localized or medium-sized basins. By contrast, TMBM addresses mega-basins that span multiple climatic, ecological and political zones, necessitating more complex coordination mechanisms (Giordano & Shah, 2017).

Integrated and multi-benefit focus. TWM primarily targets equitable water sharing, whereas TMBM encompasses energy production, food security, disaster risk reduction and ecological restoration within its scope (Sadoff & Grey, 2002; Zeitoun & Mirumachi, 2008).

Adaptive and resilient governance. TMBM frameworks are designed to be dynamic, integrating climate change adaptation, hydrological variability and scenario-based planning – a step beyond the more rigid treaty-based structures found in conventional TWM (Pahl-Wostl et al., 2023; Rivera-Torres and Gerlak, 2021b).

Polycentric and inclusive institutions. Unlike TWM, which tends to be state-centric, TMBM promotes stakeholder diversity and institutional nesting – an approach consistent with Ostrom's theory of complex resource governance (Ostrom, 2010).

Normative orientation. TMBM is not only a technical solution, but also a normative framework aimed at transformative cooperation, ecological justice and long-term regional peace. In contrast, TWM has historically lacked this transformative vision (Warner & Zawahri, 2012).

These distinctions indicate that TMBM is more than a scaled-up version of TWM; it represents a strategically evolved governance paradigm that aligns closely with contemporary global water governance challenges.

Gaps and limitations in current TMBM implementation

Despite its promise, TMBM remains unevenly applied. The literature highlights several persistent constraints that hinder their effectiveness. Power asymmetries between upstream and downstream states continue to obstruct cooperation, particularly in basins where legal frameworks lack enforceability and dispute-resolution mechanisms (Cascão, 2009). The insufficient integration of climate adaptation strategies, especially in the Nile and Mekong basins, undermines the resilience of governance systems to increasing hydrological variability (Deribe et al., 2024). Furthermore, gender equity and social inclusion are rarely mainstreamed into transboundary governance processes, despite their critical importance to long-term legitimacy and equitable decision making (Sultana & Loftus, 2012). Financial dependency on international donors also poses challenges, as externally driven agendas may weaken local ownership and reduce institutional sustainability (Warner & Zawahri, 2012). Addressing these gaps will require revisiting outdated legal instruments, strengthening participatory mechanisms at multiple levels, and embedding sustainability and justice considerations into the core of the TMBM framework.

Contributions and implications

This review contributes to the evolving scholarship on transboundary water governance by offering a conceptual framework for the TMBM grounded in real-world examples. It highlights practical strategies such as adaptive institutions, benefit-sharing models and participatory structures that can be replicated or adapted in other mega-basin contexts. The results align with the Sustainable Development Goals (SDGs), particularly SDG 6.5 (implementing integrated water resources management at all levels, including transboundary cooperation).

The complex interplay between conflict and cooperation marks the global landscape of transboundary basins. Climate change and escalating demand for water resources exacerbate these challenges and underscore the urgent need for effective management strategies (Jayaram & Sethi, 2023). The IWRM principles have emerged as a pivotal framework that advocates a coordinated approach to managing water, land and related resources. This approach optimizes economic and social welfare equally while safeguarding the sustainability of water resources (Shukla et al., 2024). The Results section highlights several examples, such as the Nile and Colorado River basins, where governance mechanisms have successfully embedded IWRM principles to navigate complex upstream-downstream dynamics, fostering cooperation among riparian nations.

Governance and policy frameworks are critical for mediating transboundary water cooperation (Jager, 2016). International laws and agreements provide the foundation for developing strategies for effective resource management, as illustrated by the benefit-sharing model of cooperative hydropower development in the Senegal basin and Mekong basin (Alam et al., 2009). Stakeholder engagement and robust institutional frameworks further ensure inclusive decision making and the successful implementation of water management initiatives (Akhmouch & Clavreul, 2016). The results highlight that the adaptive legal framework, as seen in the Colorado River basin, has successfully mitigated conflicts and promoted equitable resource distribution (Robison et al., 2014); which

underscores the potential of the TMBM to shape policies that promote sustainable development and regional peace.

Conclusion

This review examines how TMBM frameworks grounded in the principles of IWRM can advance sustainability, equity and cooperative governance in large-scale international river basins. Drawing from four prominent case studies: the Nile, Colorado, Mekong and Senegal River basins, alongside cross-cutting insights from a broader literature base, reveal that TMBM represents a significant evolution beyond traditional TWM paradigms.

TMBM emphasizes multi-benefit planning, stakeholder inclusivity, institutional adaptability and long-term ecological resilience. When implemented effectively, it facilitates equitable benefit-sharing, enhances regional trust and enables coordinated responses to climate and development pressures. However, ongoing challenges such as political asymmetries, legal ambiguities and insufficient integration of climate and social justice concerns continue to limit its full potential.

The findings suggest that future efforts to operationalize TMBM must move beyond technocratic planning to embrace more inclusive, polycentric and normatively grounded governance models. Strengthening transboundary institutions, mainstreaming equity considerations (including gender and marginalized communities) and fostering joint data sharing platforms are essential steps. Moreover, international legal instruments and donor agencies must adapt to support bottom-up processes and long-term capacity-building. By synthesizing both conceptual advances and empirical experience, this study contributes to the growing body of knowledge on transboundary water governance. It offers a roadmap for transforming mega-basin cooperation into a driver of sustainable and equitable development.

Future research on TMBM should extend beyond descriptive case studies to incorporate comparative and longitudinal analyses that assess governance effectiveness across regions and times. It is essential to operationalize the concepts of equity and justice, particularly in relation to gender, indigenous rights and intergenerational fairness. Climate change adaptation remains underexplored in basin governance, underscoring the need for studies that evaluate institutional responses to hydrological variability and extreme events. Furthermore, integrating emerging technologies such as remote sensing, artificial intelligence (AI) and blockchain for water data sharing and planning presents a promising area of inquiry. Research on sustainable financing mechanisms, including payment for ecosystem services and public–private partnerships, could help address long-term financial constraints in basin cooperation. The roles of non-state actors, informal diplomacy, and civil society engagement warrant a deeper investigation, particularly in politically sensitive basins. Finally, there is an urgent need for the development of robust monitoring and evaluation frameworks, along with increased attention to understudied mega-basins such as the Congo, Amazon and Brahmaputra, to expand the geographic scope of global water governance research.

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To enhance the language of the article, we have utilized Grammarly (https://app.grammarly.com/).

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