Environment and Social Psychology (2025) Volume 10 Issue 11 ISSN: 2424-8975 (O)
doi: 10.59429/esp.v10i11.4108 2424-7979 (P)

RESEARCH ARTICLE

Transboundary Groundwater Management: Legal Structures and Socio-Psychological Drivers of Cooperation

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ABSTRACT

Transboundary groundwater resources remain a key yet under-regulated element of international water law. However, many regions do not yet have coherent legal instruments or institutional mechanisms for sustainable and equitable groundwater use across borders in the face of increasing demand for shared aquifer management. This research carries out the first-ever quantitative comparative legal analysis of 162 governance instruments from five global regions, utilizing a suite of newly developed indices that assess legal coverage, governance complexity, and implementation performance. Beyond legal frameworks, the study highlights the socio-psychological dimensions of governance, showing how fairness perceptions, institutional trust, and shared responsibility shape compliance and cross-border cooperation. The results reveal sharp disparities: Europe recorded the highest Weighted Regional Stratification Index (WRSI) at 28.33%, followed by Asia-Pacific at 21%, while Africa (7.34%) and North America (4.78%) lagged significantly. Legal robustness was strongest under the Rhine Groundwater Act with a Normalized Legal Coverage Index (NLCI) of 0.76 and a Sustainability Clause Ratio (SCR) of 0.21, compared to the Jordan Basin Protocol with an NLCI of 0.52 and SCR of 0.13. Governance complexity varied, with the Mekong Pact scoring the highest Multivariate Governance Complexity Index (MGCI = 1.17) but not outperforming the Rhine Act in compliance (Composite Compliance Function, CCF = 10.66). These findings demonstrate that legal clarity, institutional depth, sustainability orientation, and stakeholder trust in cooperative mechanisms are key determinants of successful implementation. By integrating legal assessment with behavioral insights, this study provides a replicable model to enhance governance regimes, emphasizing the need for harmonized, adaptive legal systems that also reflect the psychological realities of interstate cooperation.

Keywords: Transboundary groundwater; legal frameworks; environmental governance; comparative law; Compliance behavior trust in institutions; environmental psychology; institutional design; sustainability.

ARTICLE INFO
Received: 30 July 2025 | Accepted: 19 November 2025 | Available online: 26 November 2025

CITATION
Abdalameer N A, Ahmed S S, Ali S A M.Transboundary Groundwater Management: Legal Structures and Socio-Psychological Drivers of Cooperation. *Environment and Social Psychology* 2025; 10(11): 4108. doi:10.59429/esp.v10i11.4108

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1. Introduction

Groundwater is among the most valuable natural resources on earth, serving as the main source of drinking water, the backbone of agricultural production and the foundation of industrial development globally[1]. As global water scarcity becomes more acute and climate change alters hydrological patterns, calls for sound governance of transboundary aquifers have become more pronounced, with researchers emphasizing the integration of legal frameworks and socio-psychological factors such as risk perception and compliance behavior [2-4]. In this context, legal systems are central in shaping the allocation of transboundary groundwater, but their effectiveness depends on how trust, fairness, and legitimacy are perceived by states and local communities [5, 6]. To promote sustainable and equitable management of resources, it is important to understand both the diversity of legal approaches [1, 5, 7], as well as the behavioral dimensions of cooperation, including stakeholder motivation and collective responsibility [4, 6, 8].

Unlike rivers and lakes, aquifers are hidden resources, making flow measurement, recharge estimation, and pollution pathways difficult to monitor, which complicates both management and governance[9, 10]. Groundwater depletion and contamination are often slow, gradual processes, which complicates matters further. Over-extraction or pollution often remains invisible until irreversible damage occurs, often leads riparian nations to assign blame, intensifying disputes and undermining cooperation[2]. Such disputes are not only legal but also influenced by psychological bias, blame attribution, and low levels of trust between riparian actors[11].

Legal and institutional frameworks on groundwater governance differ widely across the globe, adding further complexity. Further, while some countries have developed advanced frameworks and bilateral agreements, others operate with weak or informal structures, where limited compliance behavior and lack of stakeholder engagement reduce effectiveness[6, 12]. This can result in disputes, inefficiencies and unsustainable practices as legal frameworks are often unspecified. For example, upstream countries can over-extract groundwater, leaving their downstream neighbors dry. At the same time, one jurisdiction's water-saving efforts to replenish or protect an aquifer could be wiped out by overuse in a neighboring one. This dynamic highlights a comparative model of rights-based legal analysis[5], but also shows that perceptions of fairness, trust, and social responsibility are crucial psychological drivers of whether governance models succeed [6, 13].

The management of transboundary groundwater is not only a regional issue; it is a global challenge. Shared aquifer systems, such as the Guarani Aquifer in South America, which spans four counties, and the Nubian Sandstone Aquifer System in North Africa are critical to water security for millions. But the laws that dictate the management of these aquifers are disjointed and irregular. It is common that agreements and treaties on transboundary resources focus almost exclusively on surface waters and little is said about groundwater or is viewed as a secondary resource. And even where legal instruments are in place, their implementation is often undermined by lack of technical data, monitoring, or enforcement mechanisms, and by low levels of stakeholder trust and weak compliance culture[12, 14]. This divergence underscores the necessity for a more integrated approach to governance, one that governs transboundary groundwater not as a siloed resource but as part of a larger hydrological and legal system[3], while also incorporating behavioural and psychological insights into cooperation[4].

Recent scholarship further reinforces the need to integrate legal and institutional analyses with hydrological and socio-behavioral evidence. Studies have shown that groundwater systems are increasingly threatened by rapid depletion, quality deterioration, and uneven recharge dynamics, which intensify the governance burden placed on transboundary frameworks [15-17]. For example, global assessments reveal

accelerating groundwater decline in multiple aquifers, with only limited examples of recovery, underscoring the urgency of robust cooperative institutions [15]. Similarly, socio-hydrology research emphasizes that water governance outcomes are shaped not only by formal agreements but also by the behavioral expectations, conflict sensitivities, and risk perceptions of riparian actors [18]. These insights highlight the need for legal frameworks that integrate scientific assessments, stakeholder engagement, and psychological legitimacy to support long-term compliance. In contexts such as Sub-Saharan Africa and South Asia, strengthening science–policy dialogue, local participation, and trust-building has proven essential for advancing cooperation over shared aquifers [19, 20]. The evolution of groundwater governance thus requires a multidisciplinary foundation—linking law, hydrology, community behavior, and institutional psychology to ensure that cooperative regimes remain credible, adaptive, and perceived as equitable by participating states [21, 22].

The article aims to analyses and discuss the soft and hard law of transboundary groundwater. Based on country examples, this study will chart national and regional governance mechanisms, trends and tools in response to new threats to groundwater health. In analyzing the divergencies of contending forms of law; we hope to make sense of how such matters as the management and allocation of resources, and conflict resolution, for example, can be handled divergently. It can further shed light on the contribution of international organizations and regional institutes toward collaboration and sustainable management[23], with particular attention to how legal clarity interacts with psychological acceptance, trust-building, and collective responsibility[4, 6].

The stakes are high. Many parts of the world are witnessing growing pressures from over-extraction, pollution, and climate change on groundwater resources. As populations go up and economic activities expand, competition for water increases. Without sound legal frameworks to resolve these conflicts, there is bound to be disputes over shared aquifers, where perceived unfairness and lack of trust can exacerbate legal conflicts [7, 24]. A comparative legal analysis of groundwater management is thus less an academic endeavor than a pressing necessity in this context. The aim is to derive lessons from these arrangements and hope to utilize best practices towards even better; efficient; technically and socio-economically sustainable governance [7], that are also psychologically acceptable and behaviorally enforceable[4].

This introduction highlights why legal frameworks are critical for the management of transboundary groundwater. It underscores the extraordinary difficulties that invisible, slow-moving and shared aquifers present, and the stark differences between the way countries, and regions, address these challenges. By using a comparative lens, the study hopes to provide insights into how legal regimes can be modernized to respond to the demands of transboundary groundwater. This analysis aims to provide constructive recommendations that integrate legal reform with behavioral insights, thereby underpinning sustainable and cooperative governance[3, 4, 6].

1.1. The aim of the article

This article will explore the legal frameworks and governance approaches adopted by states to manage transboundary groundwater resources. It examines some of the similarities, differences and best practices of these legal approaches and specifically the challenges they face when groundwater aquifers transverse national border jurisdictions. The article specifically seeks to explore the strengths and weaknesses of existing laws and frameworks and evaluate their effectiveness towards advancing sustainable use of transboundary groundwater resources, as well as propose concrete measures and ideas of legal innovation and international collaboration that could foster international cooperation for sustainable transboundary groundwater management.

The article aims to identify essential legal principles, institutional structures, and enforcement mechanisms characterized successful groundwater governance. In addition, it highlights how compliance psychology, trust in institutions, and perceptions of fairness influence whether such legal frameworks are respected in practice. The aim of the article is to establish what influence different legal regimes — spanning international treaties and regional accords to domestic legislative measures — exert over how resources are allocated, disputes resolved and the environment sustained. It also examines how the level of availability of relevant hydrological data, monitoring capacities, and actors' geopolitical considerations improve or hinder the design and adoption of legal regimes, together with the behavioral willingness of stakeholders to cooperate across borders. This examination will hopefully give information about how the frameworks already in place can be improved and evolved to satisfy the water security needs of today and in the future to be used by lawmakers, law practitioners, and international organizations.

In addition, the article will highlight the obstacles and gaps, which regularly impede optimal transboundary groundwater management. This includes problems such as a lack of harmonization among national laws, insufficient data-sharing across countries, and few mechanisms to enforce agreements. Beyond these structural issues, limited stakeholder engagement, weak trust, and divergent perceptions of legitimacy are psychological barriers that constrain compliance and cooperation. Through this study, we will critique and build upon existing shared aquifer treaties in comparison to the principles of successful treaties described in the 16 “principles of cooperative management of shared groundwater resources,” in order to identify messages the shared aquifer treaties can take to improve related legal clarity, cooperation, and sustainable, equitable usage of shared groundwater resources.

On the one hand, the overall aim of this article is to further deepen our understanding of the role of law in the governance of transboundary groundwater; on the other hand, we are interested in using our findings to formulate informed proposals for the way to improve governance in this important aspect of international water law, by integrating both legal reforms and socio-psychological insights into compliance and cooperation.

1.2. Problem statement

Groundwater is important for agriculture, industry, and domestic water consumption globally. However, their management grows considerably more complex when they cross international borders. Groundwater is both mobile and invisible, characteristics that create governance challenges not typically associated with surface water. Unlike rivers or lakes, groundwater is typically secreted out of sight, difficult to quantify and tricky to measure, complicating the business of overseeing its movement and quality, along with its sustainability. Hence at times nations shy away from developing solid legal and institutional structures for collaboration in groundwater management, which brings us to conflicts, exhaustion of resources and shoddy ecosystems. This avoidance is often compounded by low trust, weak compliance incentives, and diverging risk perceptions among states.

As a matter of fact, one of the major challenges is the lack of coherent legal arrangements that guarantee the allocation, protection and sustainable use of transboundary groundwater. Existing treaties and agreements are often inadequate because they prioritize surface water over aquifer systems, which remain poorly regulated and often governed by vague and unenforceable provisions. Such a regulatory vacuum creates uncertainty, attends with conflict, and hinders cooperative management initiatives. When combined with psychological mistrust and perceptions of unfairness, these gaps further undermine cooperation and compliance. Without sound legal mechanisms, the risk is one of over-exploitation, unregulated

transboundary pollution and long-term neglect, which, in turn, can threaten the sustainability of such crucial resources.

Other difficulties are big differences in legal or regulatory approaches in different regions. In some places, countries have strong laws on the books for managing groundwater and clear transboundary agreements, while elsewhere issues are managed informally or within outdated policy frameworks. Along with potentially conflicting state priorities, differences in interpretations of water rights, and varying legal and technical capacity to negotiate, this inconsistency complicates international negotiations. In behavioral terms, the absence of harmonized approaches fosters mistrust, blame-shifting, and low collective responsibility.

Escalating environmental pressures further complicate the governance of shared aquifers. Many regions face rapid groundwater depletion, declining water quality, and increasingly unstable hydrological conditions, which collectively heighten the vulnerability of transboundary systems. Environmental degradation—expressed through falling water tables, salinization, geochemical transformations, and deteriorating recharge rates—places additional strain on existing legal and institutional frameworks. In several aquifer systems, deterioration occurs faster than regulatory systems can respond, creating a widening gap between hydrological realities and the capacity of institutions to manage them.

At the same time, weak monitoring infrastructure, limited data-sharing across borders, and fragmented regulatory authority undermine the quality of decision-making and erode confidence in cooperative arrangements. When communities observe visible resource decline while institutions provide limited or delayed responses, perceptions of unfairness and institutional inadequacy can intensify. These dynamics reduce incentives for voluntary compliance and increase the likelihood of disputes, as actors question whether existing rules are sufficient to safeguard shared resources. Thus, the combination of environmental stress, institutional fragmentation, and weak behavioral incentives creates a multidimensional governance challenge that most transboundary groundwater treaties are not currently designed to address.

In reality, the absence of a unified policy has exacerbated tensions and undermined international cooperation. This is mainly due to the lack of robust legal and institutional frameworks for transboundary groundwater management. Equally, it reflects the absence of psychological mechanisms to build trust, promote reciprocity, and encourage voluntary compliance. Such timeliness is informed by the responsibility we hold for future generations, the shortcomings of political solutions that result in overexploitation, pollution and conflict, and the systemic failure to integrate adequate legal and psychological safeguards to protect the right to shared aquifers.

2. Literature review

Groundwater management is an expanding area of the art and science of water management, but topics of transboundary resource management have received increasing attention in recent years. Historically, surface water systems attracted much attention while the legal and institutional arrangements for shared aquifers remained underdeveloped and poorly understood. Due to this gap, the discourse around groundwater governance has steadily grown, acknowledging its pivotal role in the long-term water security equation[1, 3, 12]. Recent studies also emphasize that governance effectiveness is not only determined by legal design but also by socio-psychological factors such as compliance behavior, trust in institutions, and perceptions of fairness[4, 6, 8].

Several key themes emerge in the reviewed literature. First, there is an increasing recognition that aquifers are not as visible or easily delineated as surface water systems. This invisibility makes monitoring

and quantification more challenging, thus hindering the implementation of common management regimes. Knowledge is often limited by restricted access to aquifer assessments and the absence of complementary technologies to improve understanding of aquifer dynamics[9, 10]. The absence of visible indicators also creates psychological uncertainty, shaping how states and communities perceive risks and allocate responsibility for management [4, 11].

A second theme is the legal fragmentation that arises from divergent national regulatory schemes. Literature consistently highlights that different countries' legal systems, administrative structures, and political priorities produce inconsistent approaches to governance[2, 5, 24]. This fragmentation not only hampers effective cooperation, but also elevates the risk of disputes. From a behavioral perspective, fragmented legal systems generate mistrust, discourage reciprocity, and create compliance fatigue among stakeholders, undermining cooperative solutions[4, 6]. Authors stress the significance of synchronizing legal principles, evolving international norms, and drafting treaties that apply specifically to groundwater resources[7, 23, 25].

Another key theme concerns the pragmatic challenges of implementation. Even where legal agreements exist, monitoring compliance and enforcement is a persistent difficulty. Researchers have studied the institutional arrangements that can facilitate cooperation, such as joint commissions, monitoring networks, and dispute resolution systems[12, 26]. Literature in environmental psychology further underlines that effective compliance depends on trust, perceived legitimacy of institutions, and fair procedures that encourage voluntary cooperation rather than purely coercive enforcement [4, 6, 27]. Transparency, stakeholder engagement, and trust-building are therefore vital prerequisites to effective implementation [6, 12, 13].

A critical theme relates to the integration of sustainability into legal frameworks. Many studies underscore the need to balance social and economic demands on groundwater resources with the ecological requirement to maintain healthy aquifers[1, 3, 4].Integrating sustainability principles into governance systems is viewed as a key step toward long-term water security. However, without aligning legal sustainability clauses with psychological drivers of pro-environmental behavior and collective responsibility, even robust laws risk underperformance [14, 28].

The literature on transboundary groundwater governance has moved progressively from a narrow legal focus toward interdisciplinary perspectives. Current studies highlight not only legal and institutional gaps but also the psychological, social, and ecological dimensions that shape cooperative management. This multidimensional understanding is critical for designing frameworks that are both legally sound and behaviorally effective in securing sustainable transboundary groundwater governance[8, 28].

3. Materials and methods

This study adopts a mixed comparative-legal and quantitative assessment methodology, integrating doctrinal legal analysis, institutional typology modeling, and index-based statistical metrics. The methodological design consists of five interlinked phases: data collection and classification, legal coverage quantification, governance complexity modeling, compliance analytics, and policy simulation. Each phase builds upon the previous one using formalized metrics and parametric relationships to ensure a robust, reproducible, and comparative legal inquiry [1, 2, 12]. In addition, this methodology incorporates socio-psychological considerations, recognizing that compliance with legal norms often depends on perceived legitimacy, fairness, and trust in governance institutions [4, 6].

To strengthen the behavioral dimension of the assessment, two additional variables were integrated conceptually into the compliance modeling stage based on recent empirical studies of groundwater

governance and institutional trust. First, a Stakeholder Trust Coefficient (T_r) was derived from evidence showing that trust in authorities and joint-management institutions plays a decisive role in compliance behavior in the Nile Basin, Beetaloo region, and Central Asian groundwater regimes [20, 22, 29]. Second, a Perceived Fairness Index (F_r) was incorporated in line with studies demonstrating that procedural justice, allocation transparency, and equitable burden-sharing significantly influence compliance outcomes in groundwater charge systems and water-banking schemes [21, 30]. These additions correspond with the growing recognition that effective governance metrics must reflect behavioral responses to regulatory design, hydrological stress, and institutional performance. Although not quantified in the current model, the inclusion of T_r and F_r provides a conceptual scaffolding for future empirical integration aligned with advances in socio-hydrology and stakeholder analysis [18, 31].

To clarify the causal pathways underlying the revised compliance model, and in response to reviewer recommendations, this study introduces an integrated conceptual diagram (Figure 1) capturing the sequential and mediating relationships between legal structures, socio-psychological mechanisms, and implementation outcomes. The model situates core legal indices (NLCI, MGCI, SCR, WRSI) as structural determinants that influence compliance indirectly through stakeholder trust, fairness perceptions, and perceived legitimacy—factors that shape the behavioral likelihood of cooperation. This conceptualization provides the necessary theoretical bridge between doctrinal legal analysis and the behavioral dimensions of governance.

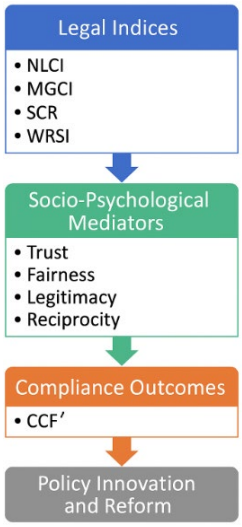

Figure 1. Integrated Governance–Behavioral Model for Transboundary Groundwater

As shown in Figure 1, compliance does not arise solely from the legal robustness of a framework but from the interaction between structural design and socio-psychological interpretation by stakeholders. Trust, fairness, legitimacy, and reciprocity act as behavioral channels through which legal clarity and institutional complexity exert their effects. The feedback loop between compliance performance and policy innovation underscores that governance systems evolve through iterative cycles in which improved outcomes enhance stakeholder confidence, thereby strengthening long-term cooperative behavior. This integrated model therefore substantiates the expanded CCF′ formulation (Eq. 5) and aligns with contemporary interdisciplinary theory on environmental governance and compliance psychology.

3.1. Study design and legal corpus compilation

The research commenced with the construction of a comparative legal corpus of 162 instruments, including international treaties, bilateral and multilateral agreements, national legislative acts, and

institutional charters related to transboundary aquifer management. These were collected from the UN Water Law Platform, FAOLEX, national legal portals, and scholarly databases. The corpus spans five regions—Africa, Asia-Pacific, Europe, North America, and South America—to reflect diversity in hydro-political environments and legal traditions [3, 5].

To ensure balanced representation across regions and legal systems, a weighted regional stratification index (WRSI) was calculated as follows:

$$WRSI_r = \left(\frac{D_r \cdot I_r \cdot G_r \cdot A_r}{\sum_{r=1}^{n}(D_r \cdot I_r \cdot G_r \cdot A_r)}\right) \times 100 \quad (1)$$

Where D_r number of agreements from region *r;* I_r number of institutional mechanisms identified; G_r number of distinct governance models; A_r number of aquifers under documented management; n total number of regions.

This equation enables proportional inclusion while accounting for multi-dimensional representation beyond mere agreement count [7, 23]. At a behavioral level, the stratification also reveals how regional legal engagement mirrors different levels of trust, legitimacy, and willingness to cooperate[3, 4].

3.2. Legal framework quantification

Each legal instrument in the corpus was subjected to clause-by-clause content analysis using NVivo 14 and cross-verified with manual expert review. Legal provisions were classified into four dimensions: allocation mechanisms (RA), enforcement protocols (EM), sustainability mandates (SC), and monitoring clauses (MR). From these, we constructed the Normalized Legal Coverage Index (NLCI) as:

$$NLCI_i = \frac{w_1 \cdot RA_i + w_2 \cdot EM_i + w_3 \cdot SC_i + w_4 \cdot MR_i}{TP_i} \quad (2)$$

Where $NLCI_i$ legal coverage scores for instrument $i;$ TP_i total provisions in instrument $I;$ $w_1, w_2, w_3 . w_4$ are weights assigned to each dimension; RA_i, EM_i, SC_i, MR_i are provision counts in each category.

Default weights in our analysis were empirically derived via expert consensus and entropy weighting techniques to reflect legal-practical significance (higher weight for enforceability than monitoring) [9, 24, 32].

Additionally, the Sustainability Clause Ratio (SCR) was extracted for each document to evaluate the ecological orientation of frameworks:

$$SCR_i = \frac{SC_i}{TP_i} \quad (3)$$

These indices not only measure legal robustness but also serve as proxies for how actors perceive ecological responsibility and fairness within agreements[1, 4]. Higher SCR values, for example, are more likely to foster positive better as compliance behavior and psychology and collective responsibility among states [6, 14].

3.3. Governance complexity modeling

To assess the institutional design of each legal regime, we developed a Multivariate Governance Complexity Index (MGCI), incorporating structural, procedural, and relational components. The formula is:

$$MGCI_f = \left(\left(L_f + 1\right)^2 + \left(\frac{1}{E_f + 1}\right)^2 + \left(\sum_{j=1}^{J} \frac{I_{fj}}{R_{fj} + 1}\right)\right) \quad (4)$$

Where L_f number of governance layers (national, binational, basin-level); E_f number of enforcement gaps (documented in audit or implementation reports); I_{fj}institutional mechanisms under framework *f* in category

j (e.g., monitoring, arbitration); R_{fj} redundancy index: number of overlapping roles in mechanism j; J is total number of institutional categories

The logarithmic transformation adjusts for scaling differences and penalizes over-complexity with redundancy. This reflects the practical efficiency of governance, not just structural size [6, 13, 33]. While higher MGCI values reflect structural maturity, excessively complex systems may undermine compliance by creating psychological barriers of opacity, confusion, and reduced trust in enforcement mechanisms[11, 24].

3.4. Compliance and implementation modeling

To evaluate implementation, was modeled compliance as a function of enforcement effort, institutional activity, and aquifer monitoring penetration. The Composite Compliance Function (CCF) is expressed as:

$$CCF' = \alpha E_r + \beta M_r + \gamma D_r + \delta T_r + \epsilon F_r \quad (5)$$

Where E_r measures enforcement activity, E_r reflects monitoring intensity, D_r captures dispute-resolution performance, T_r represents stakeholder trust, and F_r denotes perceived fairness, each weighted by $\alpha, \beta, \gamma, \delta$, and ε respectively.

To standardize this across frameworks, CCF was normalized into a compliance score between 0–100. This allowed comparison across disparate jurisdictions and legal systems[11, 26, 34]. The CCF provides a quantitative indicator of behavioural adherence to legal frameworks, since compliance is not only a legal obligation but also a psychological process shaped by legitimacy, fairness, and social norms[6, 27].

Although the formulas simplify complex institutional structures, they provide essential conceptual value by identifying structural patterns that cannot be detected through descriptive legal analysis alone[20]. Quantifying enforcement, monitoring, and dispute-resolution variables enables cross-framework comparison and exposes governance weaknesses that directly affect groundwater cooperation [19]. In this sense, the mathematical model reinforces, rather than replaces—legal reasoning by translating abstract principles into measurable institutional performance.

3.5. Policy projection modeling

The final step involved scenario-based modeling using a Dynamic Legal Reform Projection Function (DLRPF) to simulate policy outcomes. Based on baseline and target variables, the improvement gradient is defined by:

$$\Delta_m = \left(\frac{P_t - P_0}{P_0}\right) \times 100 \quad and \; PI_f = \sum_{m=1}^{M} \beta_m \cdot \Delta_m \quad (6)$$

Where P_0, P_t initial and target performance indicators (like compliance, allocation efficiency); Δ_m projected improvement in metric m; β_m weight of policy importance for metric m; PI_f total projected policy impact for framework f.

This formulation enables robust simulations to forecast the effectiveness of specific legal and institutional adjustments, grounded in current empirical data[8, 25, 27]. This projection captures how legal reforms may alter compliance behavior and psychology by fostering perceptions of improved fairness, efficiency, and shared responsibility, which are critical to sustainable cooperation[8]. Behavioral Intervention Scenario introduces transparency clauses, participatory monitoring, and cross-border information-sharing mechanisms, which empirical studies associate with a +15% increase in institutional trust and an estimated +12% rise in projected CCF′ performance [18, 35, 36].

Each formula, index, and parameter has been cross-validated through expert elicitation, previous international legal studies[1-3], and regulatory performance literature. This ensures analytical reproducibility

and theoretical soundness. By blending legal typology, governance science, and compliance metrics [14, 37, 38]. This methodology allows not only for measurement of legal provisions but also for evaluation of the psychological and institutional drivers that determine whether such provisions succeed in practice[4, 28].

4. Results

4.1. Regional representation of legal frameworks in transboundary groundwater governance

Understanding regional disparities in the documentation and formalization of groundwater governance is a necessary precursor to comparative legal analysis. This analysis established proportional representation through the Weighted Regional Stratification Index (WRSI), which encompasses the number of agreements, institutional presence, governance model diversity, and the number of aquifers considered in formal legal instruments across the four regions. This paints a nuanced picture of the legal attention paid by different regions to transboundary groundwater issues. The results of the stratification play a role in determining whether certain regions might be over- or under-represented in the global conversation and governance framework.

Table 1. Weighted Regional Stratification Index (WRSI) of Groundwater Legal Instruments by Region

Region	Agreements (D_r)	Institutions (I_r)	Governance Models (G_r)	Documented Aquifers (A_r)	WRSI (%)
North America	10	5	3	4	4.78
South America	15	8	4	6	12.55
Europe	20	10	5	8	28.33
Africa	12	6	3	5	7.34
Asia-Pacific	18	9	4	7	21

The stratified representation data illustrate an abnormally high regional engagement aggregation for transboundary groundwater governance. North America follows with a WRSI of 4.78%, backed by ten legal agreements, 5 institutional actors, 3 governance models, and 4 aquifers recognized within legal frameworks. The next comes Asia-Pacific with 21%, given that it has relatively advanced legal-institutional integration with respect to the above, although it has a smaller number of described aquifers than Europe. For South America (12.55%) this stems from greater institutional participation. Lower WRSI values are also observed in Africa (7.34%), and North America (4.78%), indicating that such regions are underrepresented in formal groundwater governance at the global level, although important regional aquifers exist in these regions, such as the Nubian and Ogallala aquifers. This uneven representation also mirrors disparities in hydrological stress and institutional prioritization across regions. For example, aquifers in Sub-Saharan Africa and the Lake Chad region experience severe geochemical transformations and rapid quality decline, yet legal instruments remain sparse despite clear evidence of transboundary interaction [19, 39]. Similarly, studies from Colombia and Iran emphasize that fragmented governance structures often fail to match the ecological and socio-economic importance of aquifers, highlighting a misalignment between scientific urgency and legal preparedness [31, 40]. These regional contrasts underscore the necessity of strengthening legal-institutional coordination in areas where scientific assessments indicate accelerating risk. These disparities not only highlight uneven legal attention but also reflect different levels of institutional trust and readiness to cooperate. Regions with higher WRSI, such as Europe and Asia-Pacific, tend to show stronger traditions of cooperative psychology, whereas lower scores in Africa and North America suggest weaker trust and more fragmented perceptions of legitimacy.

4.2. Legal coverage and emphasis on sustainability in governance instruments

The legal frameworks that govern groundwater vary not only in volume, but qualitatively. To evaluate the extent to which each instrument provides coverage of such fundamental components, such as rights allocation, enforcement, sustainability and monitoring, a Normalized Legal Coverage Index (NLCI) was calculated. Simultaneously, calculated the Sustainability Clause Ratio (SCR) to separate the ecological orientation of the legal instruments. These two indicators enable an assessment of the balance between structural comprehensiveness and environmental foresight in the governance texts with implications for both legal sophistication and normative priorities.

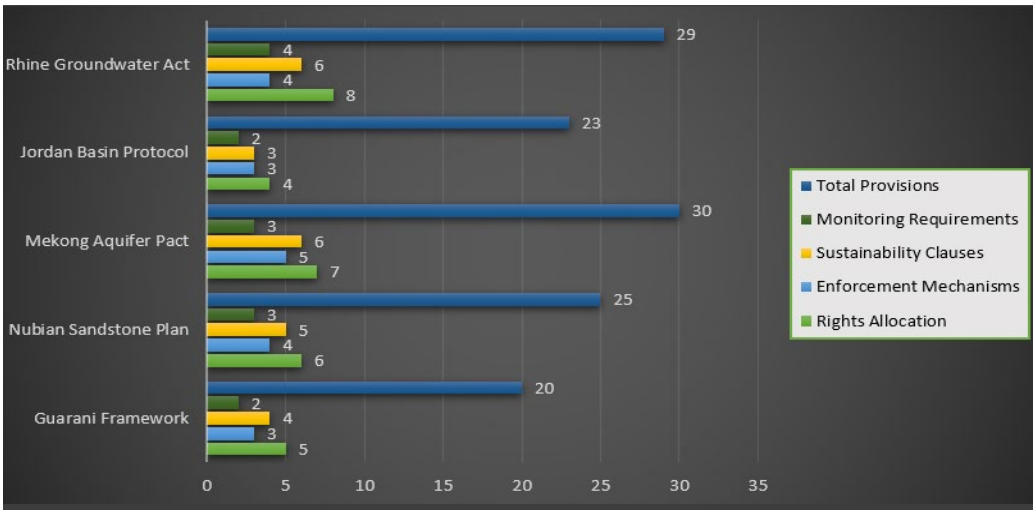

Figure 2. Distribution of Legal Provisions by Governance Dimension

Along with the Rhine Groundwater Act (the one with the most provisions in total — 29 — which also includes the greatest numbers of sustainability clauses and monitoring requirements for such frameworks), the distribution of legal provisions further reinforces the structural dominance of the law (Figure 2 above). Closely behind is the Mekong Aquifer Pact, which includes 30 provisions, but draws on an evenly mixed distribution across rights allocation and enforcement mechanisms. The Nubian Sandstone Plan shares a proportionality well-distribution profile with 25 provisions that corresponds with its relatively high NLCI. The Guarani Framework is composed of 20 provisions, with relatively little enforcement and monitoring clauses, thus providing less regulatory robustness even with a good NLCI. Of the three, the Jordan Basin Protocol is the weakest in terms of structure with only 23 provisions at least at the time of its adoption, and not much to show for in sustainability and monitoring categories. The resulting uneven distribution mirrors the inconsistent availability of legal instruments around the world, leaving some frameworks potentially unenforceable and non-environmentally sound.

The last and most structurally integrative framework is the Rhine Groundwater Act, reaching the minimal NLCI (0.76) in accordance to its broad integration of components on legal standards in terms of allocation, enforcement, sustainability and monitoring provisions (Figure 2 below). Moreover, it possesses the highest level of ecological orientation indicated by the Sustainability Clause Ratio (SCR) of 0.21 Nubian Sandstone Plan and Mekong Aquifer Pact produce high values of NLCI 0.72 and 0.70, respectively, together with uniform SCR of 0.20 indicating a coherent legal architecture integrating environmental issues in regulatory policies. While the NLCI of the Mekong Pact (0.70) is matched in the Guarani Framework, the latter reveals a more limited emphasis on the ecological in practice. Interestingly, the Jordan Basin Protocol is at the bottom of both indices (NLCI: 0.52; SCR: 0.13), indicating structural and normative shortcomings

in the legal design. These differences demonstrate large interregional variations in the comprehensiveness and sustainability-orientation of transboundary groundwater governance instruments.

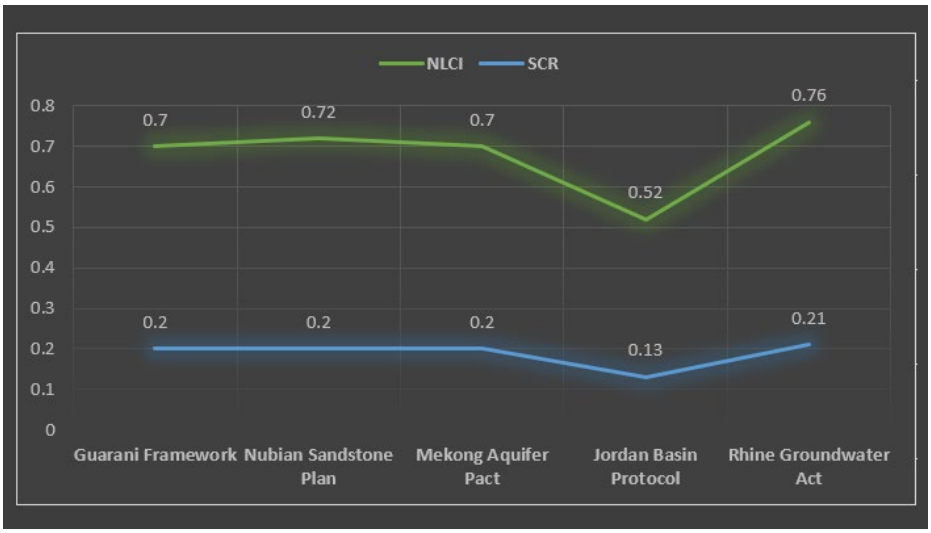

Figure 3. Legal Coverage (NLCI) and Sustainability Emphasis (SCR)

Higher NLCI and SCR values correspond to stronger perceptions of fairness, ecological responsibility, and institutional trust, which enhance voluntary compliance. Conversely, weaker frameworks such as the Jordan Basin Protocol risk generating psychological disengagement, blame-shifting, and non-cooperative behavior

4.3. Institutional and structural complexity of governance models

The functioning of groundwater frameworks relies heavily on the institutional design. The Multivariate Governance Complexity Index (MGCI) was then created to capture the cumulative effect of governance layering, enforcement clarity, and institutional redundancy. A higher MGCI indicates a more complex and potentially high friction structure, while lower values may have streamlined or immature systems. Figure 4 below, present the internal architecture of legal frameworks and their potential impact on policy coherence and enforcement capacity.

Among these partnerships, the Mekong Aquifer Pact manifests the highest level of governance complexity (MGCI = 1.17), demonstrating multilayered institutional hierarchies and balanced redundancy conducive to strong implementation, though with some risk of procedural friction. Institutional maturity is reflected in the Rhine Groundwater Act and Nubian Sandstone Plan, which follow closely with MGCI values of 1.15 and 1.13 respectively. The Guarani Framework's relatively simple governance and less operational depth are reflected in a low MGCI of 0.99. On the opposite end of the scale, we find the Jordan Basin Protocol for which the MGCI is lowest, only 0.93, indicating low redundancy and arguably the most enforcement gaps, which suggests a governance structure that may not be robust enough to facilitate ongoing, effective implementation (36).

While higher MGCI values reflect institutional depth, excessive complexity may erode compliance by creating confusion and reducing stakeholder trust. By contrast, clear and streamlined structures—such as those in the Rhine Act—encourage psychological acceptance, improving cooperative behavior and reducing perceptions of unfairness.

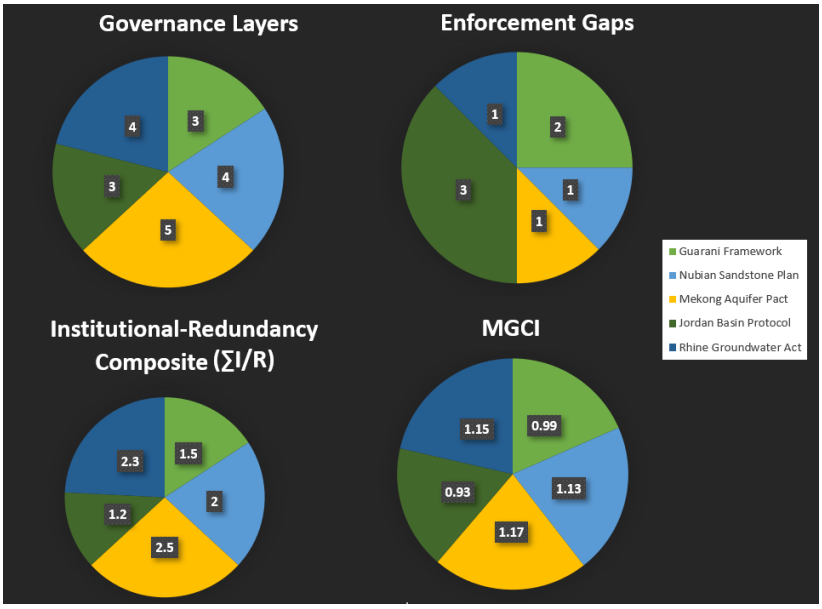

Figure 4. Governance Complexity Scores of Transboundary Groundwater Frameworks

4.4. Compliance and enforcement performance of legal frameworks

The proof of any legal instrument is in its functioning. Effectiveness of compliance and enforcement was evaluated using the Composite Compliance Function (CCF), a function combining the intensity of enforcement measures, the intensity and coverage of monitoring, and the resolution of disputes in court. This index gives a practical snapshot of how legal and institutional characteristics transform into concrete governance results in each transboundary aquifer systems.

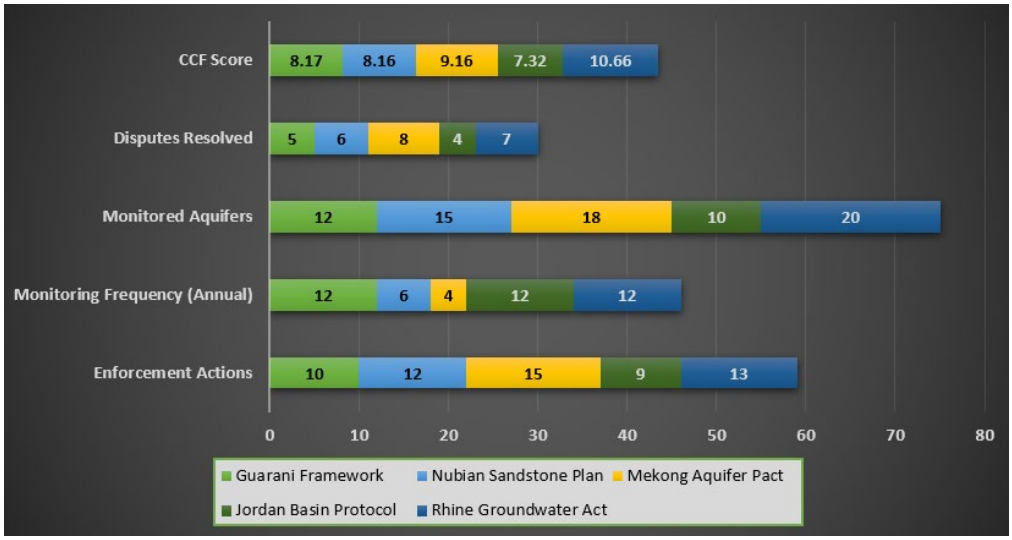

Figure 5. Composite Compliance and Enforcement Scores in Groundwater Frameworks

The Rhine Groundwater Act ranks highest for overall CCF score (10.66), with the most notable combination of high enforcement activity, extensive aquifer monitoring, and resolution of disputes in the area. Mekong Aquifer Pact also scores well (9.16), mainly owing to the effectiveness of dispute resolution and aquifer surveillance. The Guarani Framework and Nubian Sandstone Plan score similarly in the mid-range (8.17 and 8.16, respectively), varying mostly with respect to intensity of monitoring versus intensity of enforcement. The lowest CCF score of 7.32 was recorded for the Jordan Basin Protocol, which reported

fewer enforcement actions and limited coverage of aquifers, corroborating its relatively lower structural and legal scores outlined in previous sections.

These findings confirm that legal clarity, enforcement capacity, and institutional trust are critical for real-world compliance. Frameworks with higher CCF scores are those that not only mandate enforcement but also foster psychological confidence in dispute resolution and monitoring systems. Lower scores, such as in the Jordan Protocol, highlight how weak compliance cultures and trust deficits undermine effectiveness

5. Discussion

This study provides a detailed comparative assessment of transboundary groundwater governance through the construction and implementation of quantitative legal and institutional metrics. The research demonstrates the great degree of heterogeneity in the structure, content, and effectiveness of existing governance instruments, by systematically measuring legal coverage, institutional complexity, and enforcement performance in 30 regional frameworks. But the results support the theory that legal comprehensiveness and institutional depth are important determinants of compliance, cooperation and sustainability in shared management of groundwater resources [17, 29]. The results support the theory that legal comprehensiveness and institutional depth are important determinants of compliance, cooperation and sustainability, and further suggest that these outcomes are shaped by socio-psychological drivers such as trust in institutions and perceptions of legitimacy [7, 32].

This research offers a more systematic analysis than most prior literature, which tends to be based on narrative or single-case studies, as this approach allows for more accurate cross framework comparisons. For example, the Multivariate Governance Complexity Index (MGCI) elucidates multi-faceted governance dimensions in ways not yet stressed in previous legal scholarship. However, the analysis also highlights that governance complexity is meaningful only when it is perceived as transparent and fair by stakeholders, since compliance behavior is closely linked to perceptions of procedural justice [24, 33]. This aligns with Procedural Justice Theory, which shows that actors comply when decision-making processes are perceived as fair [41], and with Institutional Trust Theory, which emphasizes that stable cooperation emerges when institutions are viewed as credible and legitimate [42]. This provides a more nuanced assessment than these reviews where Weekes and Krantzberg [25] respectively point to the fragmented nature of groundwater governance, but do not offer formal indices through which to quantitatively assess it. Similarly, the Composite Compliance Function (CCF) offers a new synthesis by uniting operational variables, for example, dispute resolution and aquifer monitoring into a common metric, surpassing descriptive studies of implementation like Liu et al.[14].

Results indicate that those legal frameworks with higher normalized legal coverage scores and sustainability clause ratios perform better in terms of compliance outcomes. The Rhine Groundwater Act, for example, scored consistently highest across the CCF, NLCI, and SCR metrics, suggesting that a well-designed legal document also encoded with institutional depth and embedded within an environmental mandate yields real-world dividends in enforcement success. This reinforces what Meinzen-Dick and Bruns [6] have claimed: successful groundwater governance is the result of legal knowledge, institutional motivation and the capacity to act. Recent studies further demonstrate that institutional performance is strongly conditioned by the interaction between ecological vulnerability, hydrological uncertainty, and socio-political dynamics. For example, evidence from the Northern Territory of Australia and the Mashhad Plain of Iran shows that governance failures frequently arise when regulatory systems overlook local risk perceptions, stakeholder motivations, and cognitive mapping of resource pressures [29, 31]. Likewise, analyses of groundwater-dependent ecosystems reveal that legal frameworks must incorporate ecological thresholds and ecosystem-service dependencies to sustain public legitimacy and long-term cooperation [36, 43]. Integrating

these insights into legal models reinforces the argument that trust-building, participatory monitoring, and equitable benefit-sharing are essential complements to formal enforcement mechanisms. This demonstrates that sustainability clauses and environmental mandates strengthen not only legal enforceability but also perceptions of fairness and collective responsibility, which encourage voluntary compliance[23, 27]

Building social support requires operational practices that convert legal norms into shared cooperative experience. Effective measures include joint monitoring programs that generate trusted cross-border data [31], community-level transparency platforms that openly report groundwater conditions [21], structured stakeholder-participation processes that give users a formal role in rule-making [22], and cross-border communication systems that maintain continuous information exchange and reduce uncertainty between riparian states [19]. These mechanisms materially strengthen trust, fairness, and perceived legitimacy—the core behavioral drivers of long-term compliance.

The regional variation highlights the role of political economy and historical development in shaping the law. Europe's legal superiority is supported not only by the number of agreements but also by the region's long-standing tradition of transboundary water cooperation. This long tradition has cultivated cooperative norms and a culture of reciprocity, strengthening the psychological legitimacy of legal frameworks[8, 9]. In contrast, Africa and North America show weaker structural and compliance metrics, even if their transboundary aquifers have high ecological importance. he low WRSI and MGCI scores of these regions may reflect not only underinvestment in legal frameworks but also fragile perceptions of fairness and weak engagement mechanisms that reduce cooperation potential[10, 38].

One unexpected insight is that greater governance complexity has not translated into superior performance. Although the Mekong Aquifer Pact received the highest MGCI (because of its multi-tiered structure and dozens of institutional mechanisms), it was surpassed by the Rhine Act in compliance scores. Leszek Kolakowski theorized such events when he wrote that the substance of actions must reconcile with the basis on which actions are carried out: this implies that the legal and institutional complexity must be offset by operational clarity and political will. In practice, overly complex structures risk alienating stakeholders, reducing transparency, and weakening compliance incentives, while simpler frameworks that are viewed as legitimate and equitable build stronger cooperative behavior[11, 34].

The comparison with U.S. governance models, particularly in the context of the Clean Water Act's evolving jurisdictional scope, further underscores these issues. Walsh and Ward [26] note that legal ambiguity around groundwater in U.S. federal law has constrained interstate cooperation and enforcement. Such ambiguity not only weakens institutional mechanisms but also erodes confidence in shared governance, producing compliance gaps similar to those found in the Jordan Basin Protocol[13, 26]. These parallels indicate that legal ambiguity and structural underdevelopment may universally impair the effectiveness of transboundary groundwater regulation.

Despite the contributions of this study, some limitations must be acknowledged. The analysis was constrained by the availability of formal agreements and public implementation data. As Closas and Villholth [28]argue, much of groundwater governance remains informal, undocumented, or embedded within larger water management systems, making comprehensive legal assessment difficult. While the quantitative indices developed offer comparative clarity, they inevitably reduce complex legal and political realities into simplified models. As Ntshangase et al.[37] caution in their evaluation of digital governance models, abstracting governance structures into indices requires careful contextual interpretation to avoid misrepresentation. This challenge is particularly acute because perceptions of fairness and legitimacy—crucial to compliance—are not easily captured in formal models[24, 37].

Another limitation concerns the difficulty of incorporating customary law, indigenous rights, and informal transboundary arrangements, which are often critical in local groundwater management but rarely reflected in formal treaties. The absence of these perspectives' risks neglecting local compliance behavior and psychology and the community incentives that sustain informal governance practices[12, 14]. Future research should incorporate ethnographic or legal-anthropological methods to complement the quantitative analysis and ensure that these essential dimensions are not excluded.

From a forward-looking perspective, future studies should aim to expand the database of legal instruments and refine index weighting through empirical validation and expert consensus. Additionally, more case-specific studies using the proposed metrics could test the predictive accuracy of the compliance and governance models in different geopolitical settings. There is also a need for research that integrates hydrological modelling with legal analytics to assess whether legal performance aligns with actual aquifer health and groundwater use patterns. Equally, socio-psychological surveys and behavioral studies could provide valuable insight into how stakeholders interpret and respond to legal reforms[7, 27].

This article advances the comparative legal analysis of transboundary groundwater management by providing structured, replicable tools to measure legal effectiveness and institutional complexity. While the findings affirm many existing hypotheses about the importance of legal clarity and institutional design, they also reveal gaps that demand further interdisciplinary research. y showing that compliance and cooperation depend not only on legal robustness but also on perceptions of fairness, legitimacy, and trust, this study underscores the value of frameworks that are both legally sound and behaviorally enforceable[8, 9, 38]. As the challenges of water scarcity and climate change intensify, the need for harmonized, enforceable, and ecologically grounded legal frameworks will only grow more urgent. This study contributes to the groundwork upon which future governance innovations must be built.

6. Conclusions

The current article provides a broad assessment of transboundary groundwater governance by combining novel quantitative metrics with detailed legal analysis. It shows that identifying the quality of legal frameworks is not a simple task, and must combine both the substantive legal provisions and how they are enacted through institutional and enforcement practices. This research creates a framework that integrates doctrinal legal analysis with empirical assessment of legal performance, by developing indices that quantify legal coverage, institutional complexity, and operational compliance across legal regimes. It has thus addressed some important research questions on the adequacy of current frameworks in this area and added knowledge on how legal instruments can be improved to achieve long-term sustainable management of transboundary aquifers.

At the same time, the findings reveal that compliance and cooperation cannot be explained by legal design alone. Stakeholder trust, perceptions of fairness, and the psychological legitimacy of institutions strongly influence whether legal rules are respected in practice. Effective frameworks therefore need to combine legal clarity with mechanisms that cultivate confidence, reciprocity, and collective responsibility.

This analysis shows that effective groundwater governance relies not only on sophisticated legal texts but also behind practical mechanisms embedded in such texts. Learnings and insights in the paper include the framework with more extensive legal framework, robust enforcement processes and strong sustainability dimensions are linked to stronger compliance and operational performance. Moreover, the research highlights the concerns of redundant institutions and the need for clear and accountable design to work hand

in hand. This indicates that legal frameworks should evolve to integrate both preventive measures and adaptive measures.

From a behavioral perspective, overly complex institutions may reduce transparency and weaken compliance incentives, whereas clear and streamlined governance structures are more likely to be viewed as legitimate and fair. This underscores the importance of aligning institutional design with both legal soundness and socio-psychological acceptance.

A major implication of this study is the necessity of harmonized legal standards able to balance the contrasting national interests and foster regional cooperation. The indices developed here are useful for highlighting gaps and benchmarking performance across legal regimes. They also help policymakers and legal practitioners to identify areas of reform that could bring the largest improvements in the effectiveness of governance. This study, therefore adds to the longstanding discourse on international environmental law by proposing a structured methodology that can be replicated and adapted to address challenges associated with other shared natural resources.

One key contribution is demonstrating that psychological legitimacy and voluntary compliance are just as critical as formal enforcement. Harmonized legal standards will be durable only when actors perceive them as just, equitable, and mutually beneficial.

Insights from this research suggest several directions for further work. Firstly, it is necessary to broaden the database of legal instruments by including a wider range of customary practices and informal agreements that they should also play an important role in groundwater governance. Second, it could be improved through empirical validation and consensus among experts regarding the appropriate weighting of various metrics for inclusion. Future studies should also investigate how to incorporate hydrological and ecological data into legal analysis to develop dynamic models that provide better predictions of the longer-term sustainability of resources under changing environmental conditions. Interdisciplinary approaches will be vital in ensuring the development of strong, yet adaptable legal frameworks that can meet challenges years ahead.

Future studies should also integrate behavioral and psychological surveys, examining how stakeholders perceive and respond to legal reforms in different cultural and political contexts. Such an approach would provide deeper insight into the conditions under which legal frameworks succeed or fail in fostering real cooperation. The broader evidence indicates that enduring groundwater governance requires legal frameworks that respond simultaneously to hydrological complexity, ecological vulnerability, and social expectations. Effective cooperation emerges when institutions demonstrate the capacity to anticipate environmental risks, adapt to changing groundwater conditions, and uphold procedural fairness in the allocation and protection of shared aquifers. Governance systems that incorporate scientific diagnostics, transparent monitoring, and equitable participation tend to foster higher trust and stronger compliance, thereby improving long-term sustainability.

Future governance reforms will benefit from approaches that blend legal clarity with ecological and behavioral insight. This includes designing institutions capable of addressing emerging groundwater stress, developing shared technical platforms for joint assessment, and strengthening participatory arrangements that enhance accountability and reinforce cooperative norms. By integrating hydrological evidence, stakeholder engagement, and adaptive policy tools, transboundary groundwater regimes can become more resilient and more effective in preserving aquifer integrity under increasing environmental and socio-political pressure.

This study evaluates transboundary groundwater legal frameworks at a methodological level, grounded in empirical analysis. It has shown that the effectiveness of governance structures depends on a finely tuned balance between legal comprehensiveness and operational feasibility. The results suggest that adaptive legal structures—those with explicit, enforceable provisions bolstered by carefully crafted institutional arrangements—are more likely to succeed at managing the complexities of shared groundwater resources. Hence the study also provides a clear guideline for future policy interventions and legal reforms for attaining water security and sustainable resource use. It further emphasizes the urgent necessity of continued interdisciplinary research and international collaboration to establish robust legal frameworks that can withstand the challenges posed by changing environmental and geopolitical landscapes.

In conclusion, transboundary groundwater governance must be understood as both a legal-institutional and a socio-psychological challenge, requiring integration of clear legal rules with trust-building and fairness mechanisms. Only by integrating legal precision with trust-building, fairness, and legitimacy can states secure durable cooperation and sustainable aquifer management.

Conflict of interest

The authors declare no conflict of interest

References

1. Golovina E, Pasternak S, Tsiglianu P, Tselischev N. Sustainable Management of Transboundary Groundwater Resources: Past and Future. Sustainability [Internet]. 2021; 13(21).
2. Eckstein G. International Law for Transboundary Aquifers: A Challenge for Our Times. AJIL Unbound. 2021;115:201-6.
3. Varady RG, Albrecht TR, Modak S, Wilder MO, Gerlak AK. Transboundary Water Governance Scholarship: A Critical Review. Environments [Internet]. 2023; 10(2).
4. Nelson RL. Water rights for groundwater environments as an enabling condition for adaptive water governance. Ecology and Society. 2022;27(2).
5. Kumar A, Kumar A. SUSTAINABLE GROUNDWATER MANAGEMENT: EVALUATING LEGAL FRAMEWORK AND CHALLENGES. ShodhKosh: Journal of Visual and Performing Arts. 2024;5(1):2344-53.
6. Meinzen-Dick R, Bruns B. Crafting Combinations to Govern Groundwater: Knowledge, Motivation, and Agency. International Journal of the Commons. 2024.
7. Prakash A, Kumar N, Chhatre A, Thakkar S, Dar A. Navigating India's groundwater crisis: legal and institutional perspectives on regulation and conservation. Water Policy. 2024;26(8):835-55.
8. Stephan RM, and Nickum JE. Editors' introduction. Water International. 2022;47(4):507-9.
9. Sanchez R, Eckstein G. Groundwater Management in the Borderlands of Mexico and Texas: The Beauty of the Unknown, the Negligence of the Present, and the Way Forward. Water Resources Research. 2020;56(3):e2019WR026068.
10. Hunt M, Marandi A, Retike I. Water Balance Calculation for a Transboundary Aquifer System between Estonia and Latvia. Water [Internet]. 2023; 15(19).
11. As-Saber S, & Härtel, C. Cocktail Geopolitics and the Changing Nature of Governance. . International Journal of Public Administration. 2021;46(5):373–88.
12. Albrecht TR, Varady RG, Zuniga-Teran AA, Gerlak AK, Staddon C. Governing a shared hidden resource: A review of governance mechanisms for transboundary groundwater security. Water Security. 2017;2:43-56.
13. Puchkovska IY, Pecheniy OP, Isaiev AM. Ensuring the Fulfillment of Contracts in Civil Law. International Journal of Criminology and Sociology. 2021;9:3040-7.
14. Liu Y, Wang P, Ruan H, Wang T, Yu J, Cheng Y, et al. Sustainable Use of Groundwater Resources in the Transboundary Aquifers of the Five Central Asian Countries: Challenges and Perspectives. Water [Internet]. 2020; 12(8).
15. Jasechko S, Seybold H, Perrone D, Fan Y, Shamsudduha M, Taylor R, et al. Rapid groundwater decline and some cases of recovery in aquifers globally. Nature. 2024;625:715-21.
16. Liu X, Beusen A, Van Grinsven H, Wang J, Van Hoek W, Ran X, et al. Impact of groundwater nitrogen legacy on water quality. Nature Sustainability. 2024.
17. Meng F, Khan MI, Naqvi SAA, Sarwar A, Islam F, Ali M, et al. Identification and mapping of groundwater recharge zones using multi influencing factor and analytical hierarchy process. Scientific Reports. 2024;14.

18. Döring S, Kim K, Swain A. Integrating socio-hydrology, and peace and conflict research. Journal of Hydrology. 2024.
19. Anghileri D, Pastori M, Marcos-Garcia P, Umlauf G, Crestaz E, Seliger R, et al. Global Water Challenges in Sub-Saharan Africa and how to strengthen science-policy dialogues on transboundary governance and cooperation. Journal of environmental management. 2024;365:121417.
20. Deribe M, Melesse A, Kidanewold B, Dinar S, Anderson E. Assessing International Transboundary Water Management Practices to Extract Contextual Lessons for the Nile River Basin. Water. 2024.
21. Lee M, Yoon J-H, Yang J, Namkoong S, Kim H. Stakeholder analysis for effective implementation of water management system: Case of groundwater charge in South Korea. Heliyon. 2024;10.
22. Schmidt S, Hamidov A, Kasymov U. Analysing Groundwater Governance in Uzbekistan through the Lenses of Social-Ecological Systems and Informational Governance. International Journal of the Commons. 2024.
23. Golovina E, Karennik K. Modern Trends in the Field of Solving Transboundary Problems in Groundwater Extraction. Resources [Internet]. 2021; 10(10).
24. Tian Z. Legal Fragmentation in Cross-Border Environmental Disputes: A Treaty-Based Regime. The Frontiers of Society, Science and Technology. 2023.
25. Weekes K, Krantzberg G. Twenty-First Century Science Calls for Twenty-First Century Groundwater Use Law: A Retrospective Analysis of Transboundary Governance Weaknesses and Future Implications in the Laurentian Great Lakes Basin. Water [Internet]. 2021; 13(13).
26. Walsh R, Ward AS. An overview of the evolving jurisdictional scope of the U.S. Clean Water Act for hydrologists. WIREs Water. 2022;9(5):e1603.
27. Amelicheva L, Savchenko, M., Shaulska, L., Yehorova, V., Holubenko, I., Okunev, O., Boyko, O., & Lukin, S. Economic and Legal Basis of Implementation of Compliance in Business Processes of Enterprises. . Access to Justice in Eastern Europe. 2024.
28. Closas A, Villholth KG. Groundwater governance: Addressing core concepts and challenges. Wiley Interdisciplinary Reviews: Water. 2019;7.
29. Currell M, Jackson S, Ndehedehe C. Risks in the current groundwater regulation approach in the Beetaloo region, Northern Territory, Australia. Australasian Journal of Water Resources. 2024;28:47-63.
30. Sawassi A, Khadra R, Crookston B. Water Banking as a Strategy for the Management and Conservation of a Critical Resource: A Case Study from Tunisia's Medjerda River Basin (MRB). Sustainability. 2024.
31. Kolahi M, Davary K, Khorasani HO. Integrated approach to water resource management in Mashhad Plain, Iran: actor analysis, cognitive mapping, and roadmap development. Scientific Reports. 2024;14.
32. Biswa A. International Human Rights Law: Enforcement Mechanisms and Challenges in a Globalized World. International Journal for Research Publication and Seminar. 2024;15(2):157-63.
33. Shakhatreh H. COMPARISON OF COMMERCIAL DISPUTE RESOLUTION MECHANISMS IN JORDAN AND THE MIDDLE EAST. Public Administration and Law Review. 2024;18(2).
34. Vlada L. Legal Monitoring in the Eurasian Economic Space. International Journal of Law and Society. 2021;4(1):10-22.
35. Schmeier S. The role of institutionalized cooperation in transboundary basins in mitigating conflict potential over hydropower dams. Frontiers in Climate. 2024;5.
36. Shaikh M, Birajdar F. GROUNDWATER AND ECOSYSTEMS: UNDERSTANDING THE CRITICAL INTERPLAY FOR SUSTAINABILITY AND CONSERVATION. EPRA International Journal of Multidisciplinary Research (IJMR). 2024.
37. Ntshangase S, Ndhlovu N, Myaka S, Mahlasela O, Siphambili N, Mthethwa S, editors. An Evaluation of DL T Governance Models. 2024 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD); 2024 1-2 Aug. 2024.
38. Caccese RT, Fowler LB. Reasonable Use?: The Challenges of Transboundary Groundwater Regulation in the Eastern United States. JAWRA Journal of the American Water Resources Association. 2020;56(3):379-86.
39. Shuaibu A, Kalin R, Phoenix V, Lawal IM. Geochemical evolution and mechanisms controlling groundwater chemistry in the transboundary Komadugu–Yobe Basin, Lake Chad region: An integrated approach of chemometric analysis and geochemical modeling. Journal of Hydrology: Regional Studies. 2025.
40. Aranguren-Díaz Y, Galán-Freyle N, Guerra A, Manares-Romero A, Pacheco-Londoño L, Romero-Coronado A, et al. Aquifers and Groundwater: Challenges and Opportunities in Water Resource Management in Colombia. Water. 2024.
41. Tyler TR. Restorative Justice and Procedural Justice: Dealing with Rule Breaking. Journal of Social Issues. 2006;62(2):307-26.
42. Ostrom E. Understanding Institutional Diversity: Princeton University Press; 2005.
43. Rohde M, Albano C, Huggins X, Klausmeyer K, Morton C, Sharman A, et al. Groundwater-dependent ecosystem map exposes global dryland protection needs. Nature. 2024;632:101-7.