Official Journal of the World Water Council
Water Policy

Water Policy Vol 28 No 3, 355 doi: 10.2166/wp.2026.290

Transboundary water allocation in practice: global trends in international freshwater agreements

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ABSTRACT

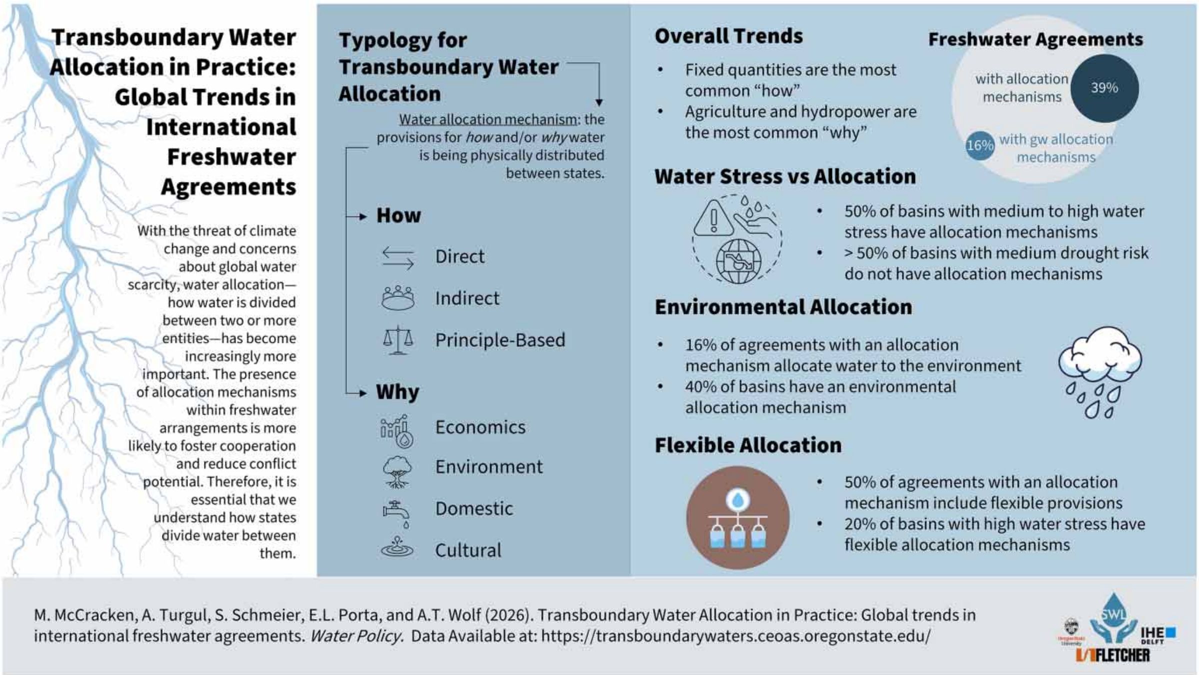
Water allocation – how water is divided between two or more entities – is addressed at many levels; however, research and policy tend to focus on the national level. At the international level, the focus is more on how actors negotiate, less on how water is physically divided. This paper fills this gap by focusing on *how* and *why* water is allocated between states. We develop the Typology for Transboundary Water Allocation to catalogue surface and groundwater allocation mechanisms within transboundary agreements, where mechanisms are separated into two components: a practical and a context component, or the *how* and *why*, respectively. Several conclusions are drawn: Over time, agreements with allocation mechanisms have increased. Groundwater-specific mechanisms and water allocated to environmental purposes have increased since the 1970s. With increasing challenges and demands on water resources, many transboundary basins still lack agreements with allocation mechanisms. Overall, the inclusion of allocation mechanisms has the potential to increase institutional capacity and, depending on their design, increase the flexibility to adapt to hydrological or socio-political change. However, the lack of allocation mechanisms or their design could contribute to potential environmental degradation, inequitable access, or conflict between states.

Key words: Allocation, International freshwater agreements, International river basin, Transboundary aquifers, Transboundary waters

HIGHLIGHTS

- Typology for Transboundary Water Allocation (TTWA) method to understand allocation mechanisms in international freshwater agreements.
- Only about 39% of agreements have allocation mechanisms.
- A limited number of agreements include allocation mechanisms for environmental purposes.
- The number of groundwater-specific allocation mechanisms is increasing.

GRAPHICAL ABSTRACT



INTRODUCTION

With the threat of climate change and concerns about global water scarcity, discussions on *how* water is shared have increased in global awareness, both within the academy and among practitioners. The allocation of water among actors has been a point of contention in many basins – and is likely to remain one – given the increasing variability brought about by climate change. Water allocation research has typically focused on domestic or sub-national policies and approaches, such as in Europe, Australia, and the southwestern United States (Patrick 2014; Garrick 2015; van Rijswick 2015; Mezger *et al.* 2019; Rey *et al.* 2019). However, over half of the world's river flow is within an internationally shared basin. There are 313 international river basins conveying nearly 60% of the world's river flow to substantial proportions of the world's population (McCracken & Wolf 2019), adding an additional layer of complexity for water allocation as it needs to span across states. At this international scale, research is much scarcer and typically focuses on how states arrive at a certain allocation but not on what this allocation actually looks like, leaving a considerable gap in knowledge. This paper, therefore, focuses on the specific mechanisms for water allocation among riparian state actors. We define a water allocation mechanism as the specific provisions that establish *how* and/or *why* water is being physically allocated, divided, distributed, or shared between states.

This paper (1) establishes a new structure – the Typology for Transboundary Water Allocation (TTWA)–for understanding the design and purpose of water allocation mechanisms in international freshwater agreements, and (2) uses this typology to conduct a global assessment of transboundary water allocation mechanisms in international freshwater agreements to identify temporal and spatial trends in the types and design of these mechanisms.

WATER ALLOCATION AT THE INTERNATIONAL SCALE

Scholarship on transboundary water allocation consists of two main threads. On the one hand, the literature often draws on international relations scholarship to broadly analyse the approaches to negotiating the process by which flows are distributed, identifying concepts such as 'rights-based,' 'needs-based,' and 'benefits-sharing' (Wolf 1999, 2009). Realist perspectives emphasize the role of power distribution and the related likelihood of a conflict or cooperative outcomes when allocating shared water resources (Conca *et al.* 2006; Brochmann 2012). Institutionalist approaches, rather, emphasize the role of joint cooperation institutions as mechanisms for allocating water. Game theory models examine how sources of political power and power asymmetries impact negotiated water allocation outcomes (Mianabadi *et al.* 2015; Jafroudi 2018; Qin *et al.* 2019). While this advances knowledge of how water allocation conversations emerge, it does not explore the specific methods used to partition water, and thus does not focus on the outcomes of such negotiation processes or how they have been put into practice.

The second main thread in the transboundary water allocation literature focuses on international water law and the international community's efforts to codify state practice, define customary legal principles, and develop soft law to guide riparian states in managing shared waters. The focal point for allocation is the substantive principle of 'equitable and reasonable use,' which is the primary rule governing transboundary watercourses (Bourne 1998; McIntyre 2013). Stemming from the duty to cooperate, the principle entitles and obliges all riparian states to use a transboundary watercourse in an equitable and reasonable manner. States should do so by 'attaining optimal and sustainable utilization…taking into account the interests of the watercourse states concerned' (UN WC Art. 5). This approach is based on considering 'all relevant factors' on a case-by-case basis. (UN WC Art. 6). Allocations based on the principle of equitable and reasonable use are considered in conjunction with other norms and legal principles, including the due diligence obligation to take reasonable measures to prevent significant harm, among others.

Despite the substantial body of work in international water law on water allocation (e.g., Benvenisti 1996; Salman 2010; McIntyre 2013; Dinar *et al.* 2015; Shubber 2023), the mechanics of allocation mechanisms have not been critically evaluated, with more focus on how allocations adhere to customary norms and how allocations can be designed in line with legal principles (Wouters *et al.* 2005; Lankford 2013; Mianabadi *et al.* 2015; Nagheeby 2024). Other institutions and nongovernmental organizations have attempted to expand these principles into toolkits for planning and developing water sharing (See Global Water Partnership and International Network of Basin Organizations 2009; Speed *et al.* 2013; OECD 2015). However, such attempts have generally focused on the domestic level or on the negotiation for allocation rather than assessing the methods that riparians use to allocate water resources between countries.

This gap, however, is particularly significant when considered in the broader context. Interstate conflict over water is most commonly about water quantity and infrastructure (Toset *et al.* 2000; Wolf *et al.* 2003; Turgul *et al.* 2024). Other studies have demonstrated that this trend is likely to continue as climate change impacts precipitation patterns and intensity alongside increasing population and economic growth (De Bruin *et al.* 2024). Furthermore, research has shown that institutional capacity, particularly the presence of allocation mechanisms within institutional arrangements, is more likely to foster cooperation and has less potential for conflict (De Stefano *et al.* 2010, 2017; Drieschova *et al.* 2010; Dinar *et al.* 2015). Yet, while this is generally the case, not all allocation mechanisms have prevented conflict and potentially have contributed to further disagreements over how much water states should receive. For example, in the Nile Basin, the historical agreements of 1929 and 1959 provide allocation mechanisms, which have led to continued disputes over the sharing of the Nile waters following the independence of the upstream states and continuing through today, as demonstrated by the refusal to sign onto the Cooperative Framework Agreement by Egypt and Sudan (Kasimbazi 2010; Dinar & Nigatu 2013; Whittington 2024). Therefore, in light of a changing climate, it is essential to understand the allocation mechanisms present in international agreements and the ways in which they divide water between states. This will provide a foundation for future work to understand which approaches are most effective at preventing or mitigating conflict, or at establishing a sustainable and equitable water-sharing regime, so that future transboundary agreements and institutions can better address the coming challenges. This paper, along with the TTWA methodology, provides this foundation.

Advances in understanding international water allocations in practice

As explained above, a thorough examination of the types of allocation mechanisms used by states in international agreements and the purpose behind these mechanisms has had little consideration in the literature. In one early work on transboundary water allocation, Wolf (1999) identified 49 treaties (of a sample of 145 treaties) with allocation mechanisms and evaluated the presence of allocation principles – such as absolute sovereignty, equal division, prioritization of uses, allocation of benefits, compensation for losses, and payments for water – to determine whether general principles, such as absolute sovereignty, territorial integrity, and equitable utilization are used in the practice of water allocation.

Subsequently, a number of studies look broadly at how allocations are defined in treaties: Hamner & Wolf (1997) established the International Freshwater Treaties Database (IFTD) as part of the Transboundary Freshwater Diplomacy Database (TFDD) housed at Oregon State University. Their research identified 145 international agreements[1], of which 68 had water allocations; of these, 15 divided water into equal portions, 39 developed ‘complex but clear’ allocations, and the remaining 14 were unclear in how water was allocated (Hamner & Wolf 1997). Giordano *et al.* (2013) updated the IFTD, bringing the database to 688 agreements. They found that water allocation was still a dominant focus and expanded on the categorization of allocation mechanisms developed under Hamner & Wolf (1997) and Wolf (1999). Giordano *et al.* (2013), following Drieschova *et al.* (2008), separated allocation into three broad categories – direct, indirect, and principle-based mechanisms. They found that 37% of the treaties[2] included a water allocation mechanism (Giordano *et al.* 2013).

This paper builds on these foundations using the TFDD’s IFTD by cataloguing and analysing the types of allocation mechanisms present in transboundary freshwater agreements today. It conducts an up-to-date global assessment of these agreements to gain a deeper understanding of the most common types of mechanisms, spatial trends, and their temporal evolution.

INTRODUCING THE TYPOLOGY FOR TRANSBOUNDARY WATER ALLOCATION

The *UNECE Handbook on Water Allocation in a Transboundary Context* defines transboundary water allocation as an ‘iterative planning and decision-making process and/or outcome that determines the quantity, quality, and timing of water at the border between two or more states and grants associated entitlements’ (UNECE Water Secretariat 2021). Therefore, allocations can be considered both a process and an outcome. We can consider transboundary water allocations as a multi-stage process with narrowing specificity and scope.

Figure 1 summarizes the stages and is adapted from the three phases of transboundary water allocation in the UNECE Handbook (UNECE Water Secretariat 2021). Most of the scholarship has focused on ‘Stage 1

[1] This is the same sample of 145 treaties used by Wolf (1999) to explore transboundary water allocation in more detail.

[2] Giordano et al (2013) utilize a lineage concept for identifying treaties along with their respective amendments, protocols, and replacements. This 37% is based on this lineage concept and is not comparable with counts from the other studies, which evaluate agreements as individual documents.

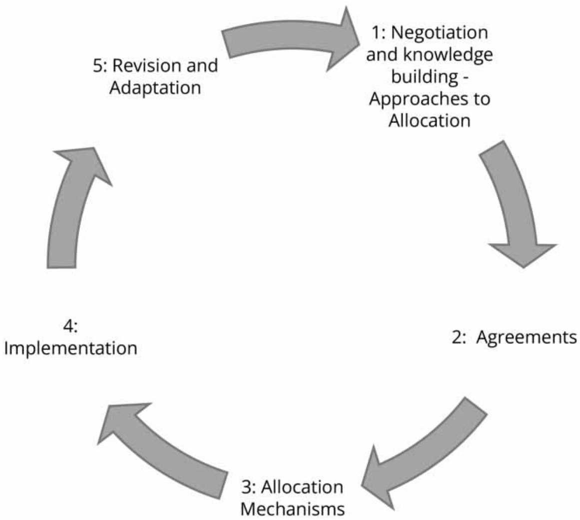


Fig. 1 | Stages within the process of establishing and maintaining transboundary water allocation (Adapted from UNECE Water Secretariat 2021).

Negotiation and Knowledge Building', which includes the approaches to allocation that influence these discussions and, ultimately, the agreements that result (Stage 2). Within the agreements signed on water allocation, there are the water allocation mechanisms (Stage 3), where allocations can be viewed as an outcome. In this context, we define a water allocation mechanism as the specific provisions that establish *how* and/or *why* water is being physically allocated, divided, distributed, or shared between the states. These mechanisms are developed as a result of the knowledge-building process and the approaches used during the negotiation of the agreement. Once the allocation mechanisms have been established, they must be implemented and then potentially refined or adapted given monitoring outcomes and changes to supply and demand (UNECE Water Secretariat 2021).

To assess these mechanisms, this paper develops the Typology for Transboundary Water Allocation (TTWA) as a method for cataloguing and understanding the mechanisms for water allocation within transboundary agreements for both surface and groundwater. The TTWA separates allocation mechanisms into two components: a practical component and a context component. The Practical Component (Table 1) captures *how* water is physically allocated, divided, or distributed among riparians within three sub-categories: direct, indirect, and principle-based mechanisms, based on the previously established classification systems for sharing water (Drieschova *et al.* 2008; Giordano *et al.* 2013). Direct mechanisms explicitly identify a means for physically dividing water into measurable quantities between the riparians, such as fixed quantities, a percentage of the flow, or an equal division. Indirect mechanisms establish procedures for determining allocations, such as prioritization of uses, a commission, consultations, or prior approval. Lastly, agreements can establish mechanisms based on principles that guide the riparians in developing allocation mechanisms, e.g., historical use, equitable use, and market-based mechanisms. Wolf (1999) noted that in the practice of negotiating allocation mechanisms 'in the room,' these principles are rarely explicitly stated. However, these principles remain visible in the specific allocation mechanisms derived from these 'in the room' processes. TTWA organizes these allocation mechanisms into categories associated with the often unstated but present principles most likely to manifest in allocation mechanisms.

The second part of the TTWA is the Context Component (Table 2), which captures the purpose of the allocation mechanism and identifies *why* the water was allocated in a particular way. For example, an agreement

Table 1 | The practical components for water allocation mechanisms within the TTWA.

Typology for Transboundary Water Allocation: Groundwater and Surface Water **Practical Component of Allocation Mechanisms**	
Direct Mechanisms	Fixed quantities: A set volume of water to each riparian; could be once, annually, or at other defined intervals Fixed quantities to only a subset of the riparians: A set volume of water is allocated to only some of the riparians, and the undefined quantity of the remainder is allocated to other parties Percentage of flow: Percentages of flow are allocated to riparian states Equal Division: Water is divided equally between the parties; equal division could be in fixed quantities, percentage, time, etc., or undefined. Variable by water availability: The allocation is dependent on the availability of water, including inter- and intra-annual variability, i.e., allocations for low or high flow, drought, or flood Variable according to time of the year: The allocation is dependent on the time of year, e.g., a monthly or seasonal schedule Water loans: This covers allocations that are recoupable in later periods, if not met, such as when a riparian is unable to meet a delivery; it can be delivered at a later period, and allocations that are able to be borrowed from another riparian and paid back at a later time. Allocation of entire/partial aquifer/river: Allocation is based on sole use, e.g., States are allocated sole use of an aquifer/river or sole use of segments/portions of an aquifer/river within their territory Allocating time: Flow is allocated to a riparian for a defined period of time Cap, limit, or no allocation allowed: Clearly defined cap or limit on the allocation allowed for the resource, and/or the text explicitly does not allow for any diversions from the resource.
Indirect Mechanisms	Consultation and/or Prior Approval: Riparians consult or seek prior approval/consent of other riparians to determine allocations, make changes to allocations already defined, or for short notice/temporary changes to allocations, such as if one party requires a higher water use than usual because of the construction of an irrigation system. RBO, Commission, and/or Committee: The allocation mechanism in the agreement is procedural. A river basin organization, commission, and/or committee is tasked with the responsibility of determining the allocation mechanism. This could include an existing body or a newly established body with a broad mandate, as well as an existing or newly established body for the specific purpose of establishing and managing allocations.
Principle-Based Mechanisms	Benefits sharing: The benefits of the allocated water are shared between parties, e.g., hydropower, flood control, or other benefits that could be given a monetary value, which is shared. This is not an exchange of water with a non-water linkage. Historical or existing uses: The allocation mechanism is based on the prior, historical, or existing uses of the riparian(s). Prioritization of uses: Allocation is divided based on the priority of use, e.g., domestic use first, hydropower second. Equitable use: Allocation mechanism is defined using the principle of equitable and reasonable use. Sustainable use: The allocation mechanism defines sustainable use for the aquifer/river or allocates water based on the principles of sustainable use. Market-based: The allocation mechanism uses a market instrument, such as a water market, to allocate water.

(*Continued.*)

Table 1 | Continued

Typology for Transboundary Water Allocation: Groundwater and Surface Water Practical Component of Allocation Mechanisms	
Not Defined	Not Defined: Allocation mechanism exists, but it is not defined.
Direct Groundwater Specific Mechanisms	Pumping rates: Allocation mechanism specifies particular rates for abstraction from wells. Water table impact: Allocation mechanism refers to or is limited by the groundwater table height. e.g., abstractions are prohibited if the water table falls below a certain level in monitoring wells. Spring outflow: The allocation mechanism is related to the spring outflow; for example, the volume of allocation is dependent on the level of spring outflow.
Indirect Groundwater Specific Mechanisms	Aquifer: Allocation mechanism is related to or addresses the pore space and/or storage capacity of the aquifer, not the groundwater itself.

Table 2 | The context components for water allocation mechanisms within the TTWA.

Typology for Transboundary Water Allocation: Groundwater and Surface Water	
Context Component of Allocation Mechanisms	Minimum flow: not specified/undefined purpose Minimum flow: navigation Minimum flow: environmental needs Minimum flow: hydropower Minimum flow: tourism/recreation Environmental/In-stream Flow Aesthetic/Tourism/Recreation Intrinsic/Cultural/Spiritual Hydropower Agriculture/Irrigation Navigation Support of Fish Habitat and Stocks/Fishing Rights Domestic and/or Municipal Uses Border/Territory Maintenance Pollution, such as a specific volume for dilution purposes Undefined Purpose Other

might divide water using a fixed volume or flow rate for irrigation purposes, or the signatories may identify a percentage of flow that needs to be maintained to meet a basin's minimum environmental needs. Other potential Context Components include, inter alia, minimum flows, hydropower, navigation, or an undefined purpose.

Additionally, the TTWA contributes a clarifying distinction between groundwater and surface water allocation mechanisms. Historically, the focus of allocation mechanisms has been on sharing surface water. With growing attention to the shared management of groundwater, there is a need for groundwater allocation mechanisms that consider the unique properties and physical characteristics distinguishing groundwater from surface water and the groundwater-specific techniques employed to abstract water. Therefore, besides separating allocation mechanisms for surface and groundwater, the TTWA also establishes several groundwater-specific practical components for how water is physically divided between states (see Table 1). These include using pumping rates, water table levels, and spring outflows to monitor or determine quantities for allocation, as well as mechanisms that divide water based on the pore space or storage capacity of an aquifer rather than based on the volume of water itself.

METHODS OF ANALYSING ALLOCATION MECHANISMS IN TREATIES

The IFTD catalogues international agreements from 1820 to 2025, with a focus on shared waters as a consumable resource. We coded 768 unique agreements within the IFTD according to the TTWA methodology to understand the most common types of allocation mechanisms in transboundary basins, as well as their spatial trends and historical evolution. We determine the breakdown of types of allocation mechanisms based on the practical (Table 1) and context components (Table 2), whether these elements apply to surface or groundwater resources, and how these resources are shared across bilateral or multilateral agreements and basins. We assess the overall counts of these factors at several levels of analysis, including the full sample, as well as the spatial and temporal distributions, and in comparison to a basin's level of water stress. We map the spatial distribution of surface water allocation mechanisms, indicating their presence or absence, to the basins and the corresponding basin country units. Additionally, we examine the variation in coverage between basin-wide agreements with allocation mechanisms and those that do not cover the entire basin. However, mapping the spatial distribution of the groundwater allocation mechanisms was not feasible given that they are limited in number and that in many agreements, the aquifers are not identified. Regional and global agreements, as well as agreements with unidentified basins, were also excluded from the spatial analysis. For the temporal analysis, we include decadal counts of the number of agreements signed per decade with an allocation mechanism and the number of allocation mechanisms included in agreements relevant to a specific decade. Agreements with unknown dates are categorised separately.

RESULTS OF THE TTWA ANALYSIS

Allocation of shared waters has been a primary aspect of transboundary water cooperation, unsurprisingly, as states need to agree on who receives how much water and when. Yet, a surprisingly low proportion of agreements have specific allocation mechanisms. Of the 768 unique agreements in the IFTD, 299 (39%) have a water allocation mechanism. Of these, 284 (95%) have a surface water allocation mechanism, and 49 (16%) have a groundwater allocation mechanism. Of the 49 agreements with a groundwater allocation mechanism, 15 (5%) exclusively address groundwater allocation, while 34 (11%) have both surface water and groundwater allocation mechanisms.

Overall results: practical and context components

The most frequent practical component of allocation mechanisms is not clearly defined, found in 69 (24%) agreements of the 284 containing a surface water allocation mechanism. *Fixed quantities* ($n = 66$), *Cap, limited, or no allocation allowed* ($n = 46$), and *RBO, commission, and/or committee* ($n = 46$) are the next most common. The *Market-Based* mechanisms are the least common, with only one agreement. Only two other Practical Components have fewer than ten documents coded ($n = 3$ each): *Allocating time* and *Benefits sharing*.

Over half of the 284 agreements with surface water allocation mechanisms (58%) do not define a purpose, which is by far the most common for the context component. Of those that do have a defined purpose, *Agriculture/Irrigation* ($n = 69$) and *Hydropower* ($n = 59$) are the most common. The least common are: *Minimum flow: tourism/recreation* ($n = 1$) and *Intrinsic/Cultural/Spiritual* ($n = 2$).

There are similar overall trends for groundwater allocation mechanisms. *Sustainable Use (n = 18)* and *Equitable Use (n = 17)* are the most common practical components. The following most frequently coded are present but not defined ($n = 14$) and *Cap, limited, or no allocation allowed* ($n = 14$). Eight practical components *(Fixed quantities to only a subset of the riparians, Variable according to the time of the year*, *Water loans*, *Benefits sharing*, *Pumping rates*, *Spring outflow,* and *Aquifer)* are not found in any agreements with a groundwater allocation mechanism.

Like surface water, most of the 49 agreements (73%) do not define a purpose for their groundwater allocation mechanisms. When a purpose is defined, it is most common for *Domestic and/or Municipal Uses* ($n = 12$) and *Agriculture/Irrigation* ($n = 8$). Five context components are not identified in any agreement with a groundwater allocation mechanism, many of which, for obvious reasons, in that they have little relevance for groundwater *(Minimum flow: hydropower*, *Aesthetic/Tourism/Recreation, Intrinsic/Cultural/Spiritual, Support of fish habitat and stocks/fishing rights, Navigation*).

Within the three sub-categories of practical components, most surface water allocations are direct mechanisms ($n = 293$), followed by principle-based ($n = 87$), and indirect ($n = 71$). This distribution differs from groundwater allocation mechanisms, where it is more even between the three; most are principle-based ($n = 42$), followed by direct ($n = 24$) and indirect ($n = 14$). Only one agreement utilized a groundwater-specific allocation mechanism.

Spatial results

When considering the spatial distribution of the allocation mechanisms, we could only map the allocation mechanisms for surface water, as noted above. Two-thirds of the 313 international river basins have a legal arrangement, but only half of the basins have at least one allocation mechanism. However, when considered from the level of basin-country units, coverage becomes more fragmented. Many multilateral basins have agreements with allocation mechanisms that do not include all the riparian states. For example, compare the Nile and Amazon River Basins, which have 11 and 7 countries in the basin, respectively. In both, there is not full coverage of allocation mechanisms across all countries, with the Nile having greater coverage at 9 out of 11 riparians for surface water mechanisms, compared to 2 out of 7 for the Amazon.

Most basins ($n = 235$) are bilateral, with only two riparian states; surprisingly, a greater proportion of the multilateral basins, shared between more than two riparians, have a mechanism for both groundwater and surface water allocation than bilateral basins. Yet, when this is broken down further, most of these mechanisms are in bilateral agreements and therefore do not include all the riparians in the multilateral basin. Of the 78 multilateral basins, 67% have a surface water allocation mechanism that specifically addresses a sub-basin area, with only 22% of them having a surface water allocation mechanism that covers the entire basin. A similar trend is found with bilateral basins, while these are inherently inclusive of both riparians signing the agreement, the spatial coverage within the basin is similarly fragmented, with only 9% of bilateral basins having an agreement with a surface water allocation mechanism covering a specific entire basin, and 17% applying to a specific sub-basin. In bilateral basins, it was more common (28%) to have broad agreements that cover all the frontier or shared waters between the two states. These surface water allocation mechanisms, therefore, vary considerably as to whether they apply to border areas of all rivers, or a singular provision for surface water allocation for just one of the shared basins.

Temporal results

Agreements in the IFTD cover the time span of 1820 to the present decade; the 1830 and 1840 s were the only decades during which states did not sign any agreements – thus, there were also no water allocations reflected in treaties this decade. In contrast, the decade during which the greatest number of agreements were signed was between 1990 and 1999 ($n = 147$). The 1860s was the first decade to contain allocation mechanisms. The

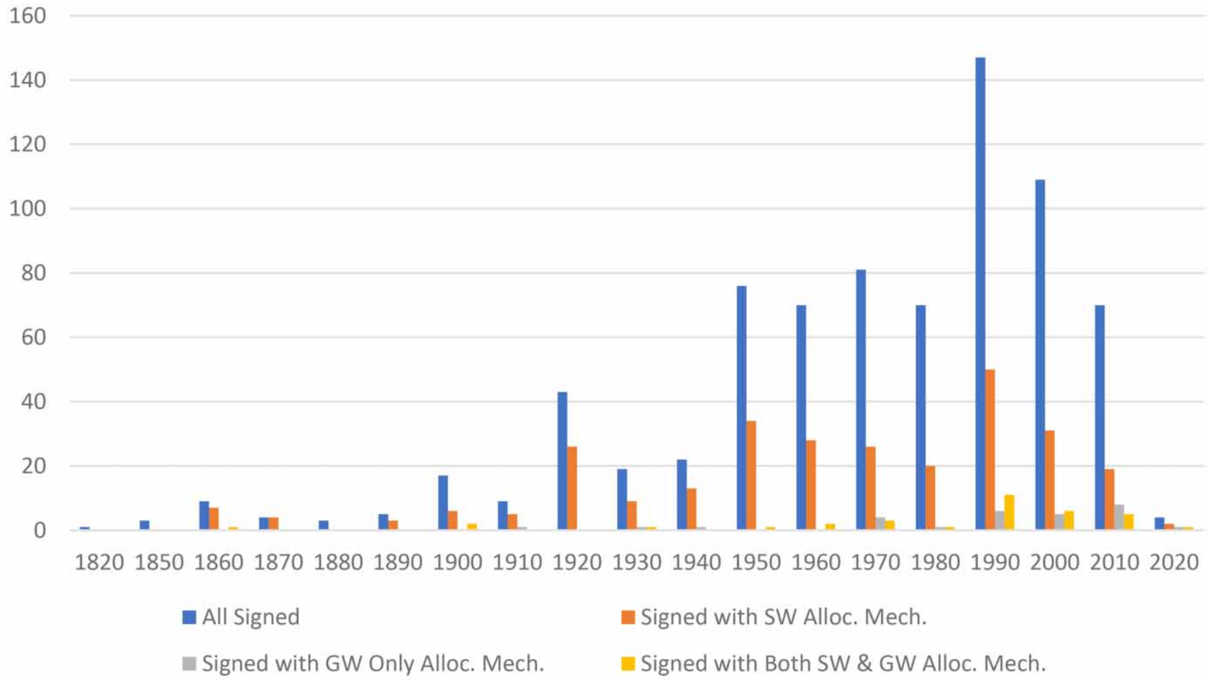


Fig. 2 | Number of agreements signed per decade, including counts of agreements signed that contained at least one surface water and/or groundwater allocation mechanism. *Note*: 2020 is a partial decade through 2025.

inclusion of surface and groundwater allocation mechanisms broadly follows the trend in the signing of agreements, with the peak in the 1990s and then a subsequent decline (Figure 2); the exception is that groundwater allocation mechanisms have been increasing in inclusion as a proportion of agreements signed. Giordano *et al.* (2013) noted in their analysis of the previous update of the IFTD that the 1990s represented a notable shift in the focus of international water documents in addressing shared freshwater resources. Possibly from the influence of multiple conferences and conventions beginning in the 1960s, environmental protection and environmental services in international water agreements increased in prominence in their assessment (Giordano *et al.* 2013). Similarly, our analysis notes the mid-century and 1990s as critical change periods in the inclusion of water allocation mechanisms, which aligns with the previously recognized pattern of environmental protection-oriented components.

The 1990s decade was a singularly high-count decade for allocation mechanisms; almost half of these were direct allocation mechanisms, and over a quarter were principle-based mechanisms. Generally, this pattern is consistent across the recorded period for surface water mechanisms: direct mechanisms are the most common allocation type. Over half of all surface water allocation mechanisms are through a direct mechanism. However, there has been a substantial shift over time away from direct mechanisms and toward more principle-based mechanisms, particularly as a result of groundwater allocation mechanisms (Figure 3). Principle-based mechanisms (particularly *Equitable use* and *Sustainable use)* are the overall most common type of groundwater allocation mechanism, with most agreements signed in the three most recent decades. This is largely due to the popularity of these mechanisms from the 1990s to the present. The 1990s were a decade of focus on environmental protection and stakeholder engagement principles. The attention to these concepts during their development period

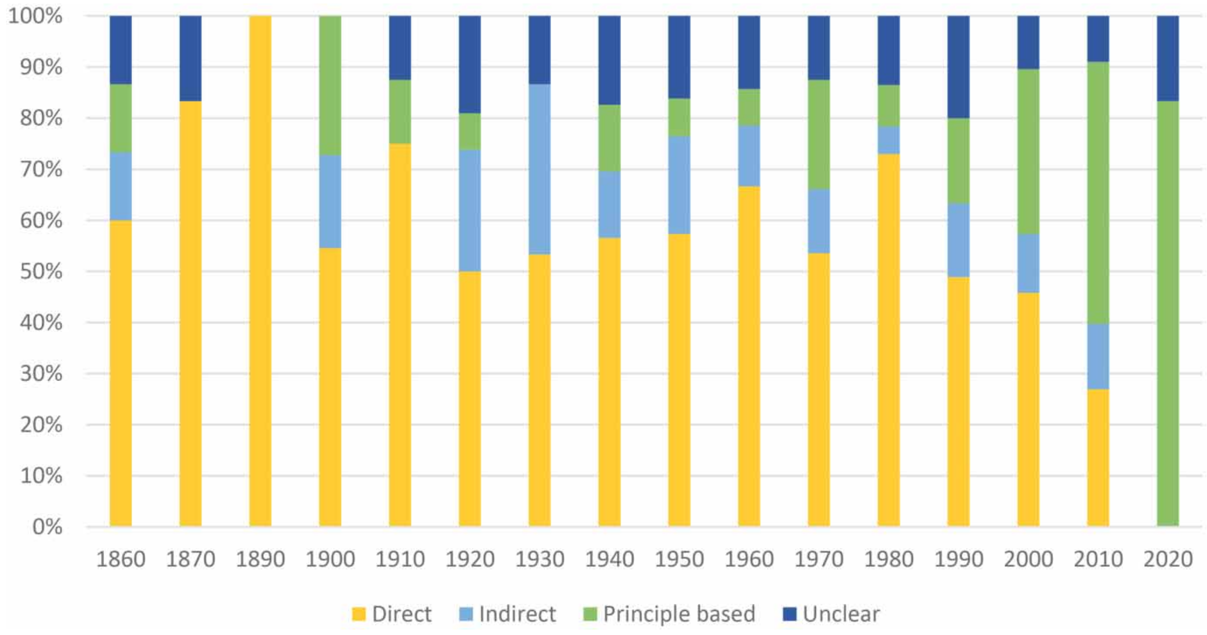


Fig. 3 | Proportion of agreements signed that decade with a surface and/or groundwater mechanism distinguished by category: direct, indirect, or principle-based.

could have influenced the dominance of this sub-category on groundwater allocation mechanisms, considering the small number in the sample. In the few instances when groundwater was allocated prior to 1990, direct mechanisms were the most popular.

DISCUSSION

Water allocation vs. water stress

With the increasing pressures from climate change, population growth, and economic development, water allocation mechanisms in transboundary basins will become increasingly more important as water stress, variability, and drought risks increase. Using our analysis through the TTWA, we compared the basins and basin country units with surface water allocation mechanisms to the World Resources Institute's Aqueduct water stress, interannual variability, seasonal variability, and drought risk (World Resources Institute 2025). Table 3 shows the proportion of basins that have a surface water allocation mechanism and their level of water stress and drought risk.

Through this assessment, we see that with current climate and demand conditions, agreements that have surface water allocation mechanisms partially cover basins across all levels of water stress. However, 28 basins with high and medium levels of water stress still do not have allocation mechanisms in place, which may contribute to future tensions, inequitable water access, or environmental decline due to unsustainable use.

There is a similar trend in terms of the risk of drought, where there is partial coverage; however, more basins are at a medium risk of drought compared to those that are currently at medium levels of water stress, yet over half (62 basins) do not have a surface water allocation mechanism. Perhaps unsurprisingly, the four basins that have the highest drought risk all have allocation mechanisms. This assessment helps identify priority basins for

Table 3 | Proportion of basins with agreements with surface water (SW) allocation mechanisms that are in a state of water stress or at risk of drought.

	Water Stress			Drought Risk		
Level or Risk	**Number of Basins**	**Proportion of all Basins**	**Proportion with SW Allocation Mechanism**	**Number of Basins**	**Proportion of all Basins**	**Proportion with SW Allocation Mechanism**
High	35	11%	49%	4	1%	100%
Medium	18	6%	61%	135	43%	46%
Low	154	49%	46%	68	22%	53%
No Data/ Arid	106	34%	n/a	106	34%	n/a

Source: WRI Aqueduct, accessed April 2025.

increasing institutional capacity to include surface water allocation mechanisms, as the risk for drought is relatively high and potentially likely to increase with further climate change.

Environmental allocations

Environmental allocations, in which water is explicitly allocated to preserve aquatic ecosystems or maintain ecosystem services, represent a growing subject of research (Mezger *et al*. 2019; Mumme 2020) and are more recent inclusions into international freshwater agreements. While a significant body of work supports environmental flow allocations sub-nationally, there have been few large-scale analyses of how environmental allocations are embedded in international freshwater agreements; the few that have focus on single case studies (Lane *et al*. 2015; Mumme 2020) or regional analyses (Acreman & Ferguson 2010; King & Brown 2010).

Under the TTWA, we identify four context components that represent different ways in which water is allocated to the environment or for environmental purposes: 1) minimum flow to maintain environmental needs; 2) an allocation is identified as an environmental flow and used to maintain ecological functions and services; 3) water can be allocated to maintain fish stocks; and 4) water can be allocated for water quality purposes. The degree of specificity, as well as which practical components of the mechanism are included with them, varies widely. For example, some agreements acknowledge that a certain amount of water needs to be left in-stream for ecological purposes, e.g., the *2002 Framework Agreement on the Sava River Basin* stipulates that the riparian countries ensure there is 'water in sufficient quantity and of appropriate quality for the preservation, protection, and improvement of aquatic ecosystems' (Article 11a). In comparison, other agreements may oblige the signatories to set aside fixed amounts or percentages of water to preserve and maintain necessary ecosystem functions. According to a 1998 agreement, Peru and Ecuador are required to ensure that a minimum flow of 0.4 m^3/sec is left in the Zarumilla River for ecological purposes. The delineation of environmental flows is important in transboundary basins, where upstream development can harm downstream ecosystems. Including environmental flow provisions into transboundary agreements supports potentially degraded ecosystems and simultaneously addresses the physical needs of people and the environment.

Of the 299 agreements with an allocation mechanism, 50 agreements have at least one environmental allocation mechanism. For the agreements with surface water allocation mechanisms, 15 set aside a minimum flow of water for environmental purposes – for example, the 1986 Treaty on the Lesotho Highlands Water Project states that a minimum of 500 and 300 L/sec of water must be left downstream of the Katse and Mohale dams, respectively. Twenty-two agreements have an allocation mechanism for environmental/in-stream flow purposes that stipulate that water must be left in the river for environmental purposes, although a specific quantity is not specified. Six allocate water to protect fish habitat, and 12 have an allocation mechanism for maintaining water quality – either limiting the amount of pollution that can be discharged into a river or mandating that a certain volume of water be used to dilute pollution. For instance, the United States and Canada established limits on the amount of specific pollutants that can be discharged into the St. Lawrence River in two separate additions to the *1978 Agreement Between Canada and the United States of America on Great Lakes Water Quality*.

Only a few agreements have groundwater-specific allocation mechanisms: three for water quality, five for minimum flow, and four for environmental/in-stream flow. For example, the Al-Sag/Al-Disi agreement bans the extraction of groundwater from a protected area for five years.

The design of the TTWA allows for comparison of the type of practical component for how water is allocated with the specific purpose that the allocation mechanism is targeted for, if defined. For environmental allocation mechanisms, the most common method for allocation is via direct mechanisms, with a fixed quantity of water being most common for all four context components, except for fish habitat, which is more common through consultations or prior approval. Surprisingly, few environmental allocation mechanisms are established via principle-based mechanisms, as environmental allocation mechanisms have been increasingly included over time since the 1950s, which is similar to the trend seen with the inclusion of principle-based mechanisms, yet they do not follow a parallel pattern.

Geographically, there is a wide variation. Of the 313 basins, only 40% have an environmental allocation mechanism compared to the 66% that have any agreement or the 51% with a surface water allocation mechanism. Most basins with environmental allocation mechanisms are located in Europe, where 73% of European basins have at least one environmental allocation mechanism. North and South America have the fewest basins that are governed by an agreement with an environmental allocation mechanism, at 20 and 5%, respectively. The purpose also varies regionally. European basins have more water quality and minimum environmental flow mechanisms, while Asian and African basins have more environmental/in-stream flow requirements. These patterns reflect the shifting discourse during which many of these agreements were signed, with European agreements generally signed earlier and more focused on the significant water quality concerns in the region, as well as those signed as a result of the Water Framework Directive. Agreements for Asian and African basins are potentially more impacted by the influence of donors in the development of agreements, therefore reflecting global discourse emphasizing environmental protection.

In addition to geography, how environmental allocation mechanisms are included in basins that are water-stressed, at risk of drought, or subject to high inter- and intra-annual variability is important to consider. Above, we noted that there is around 50% coverage of basins with high, medium, and low water stress levels by agreements with surface water allocation mechanisms. However, fewer have mechanisms to allocate water to the environment or for environmental purposes, see Table 4. This is potentially problematic, as resources become more stressed and/or overallocated, the ability to add flow for environmental purposes becomes more challenging. For example, the ongoing process to restore flow to the Colorado River Delta through the minute process under the 1944 US-Mexico Treaty. However, it is interesting to note that the relative proportions have shifted, with a greater ratio of basins with high stress or variability having environmental allocation mechanisms, compared to basins with medium and low stress or variability that are more evenly distributed for surface water allocation mechanisms overall.

Flexible allocations

Flexibility is a component of the 'adaptive capacity' of institutions or actors to respond to change, such as in hydrologic resources or from climate change, by altering socio-political or economic systems tied to natural resources (Hill 2012). This can be a broad topic with multiple ways of bringing flexibility into international

Table 4 | Proportion of basins within the respective level that have agreements with at least one environmental allocation mechanism.

	Proportion of Basins with Environmental Allocation Mechanisms			
Level or Risk	***Water Stress***	***Drought Risk***	***Interannual Variability***	***Seasonal Variability***
High	20%	25%	24%	14%
Medium	28%	13%	26%	3%
Low	6%	9%	7%	14%

Source: WRI Aqueduct, accessed April 2025.

water agreements, from how often treaties are revisited and renegotiated to specific provisions on data sharing about water resources (McCaffrey 2003; Drieschova *et al.* 2008). Flexibility in international water allocation mechanisms allows riparians to adapt to changes in their understanding of how water is best managed and shared, or changes in physical and hydrological conditions (Drieschova *et al.* 2008).

The design of the TTWA enables tracking of how flexibility is developed in allocation mechanisms, as well as the patterns in how flexibility has evolved over time and space. In line with the above definition, we identify eight practical mechanism components within the TTWA typology that are flexible in design to support water allocations to adapt to hydrological or socio-political change. They include the following direct mechanisms: (1) variable by water availability, (2) variable according to time of the year, and (3) water loans; principle-based mechanisms: (4) equitable use, (5) sustainable use, and (6) market-based; and indirect mechanisms: (7) consultations and/or prior approval and (8) RBO, commission, and/or committee. The selection of these typology components builds on previous work by Odom & Wolf (2011), who identified allocations based on percentages, time of year, and overall availability based on average annual water volumes as an initial list of flexibility mechanisms. Allocations made through the principle-based equitable and sustainable use components have the potential for (re)assessment of human needs for water alongside ecological processes, hence encouraging flexibility in how water is divided between riparians for this purpose – although de facto would be dependent on implementation and whether states are open to reassessment of allocations. Including the potential for signatories to consult with each other or establish expert panels further incorporates opportunities for changing their approach to water sharing. These mechanisms have the potential to allow international agreements to withstand change in water availability or change in demands between riparians. For instance, water loans allow countries in water-stressed or highly variable areas to maintain treaty compliance for shared flows by making up annual deficits in later years. The USA and Mexico have incorporated this mechanism into several agreements, as have countries in the Middle East and Africa, particularly in water-sparse areas.

Of the 299 treaties with allocation mechanisms, 147, or slightly over half, include one or more of these flexible practical components in their allocation mechanism(s) for sharing surface water resources. Thirty-one of the agreements included a flexible groundwater allocation mechanism. Flexibility in surface and groundwater sharing grew over time following the general pattern of treaty signing and the inclusion of allocation mechanisms, with a surprising exception: flexible allocation mechanisms for both surface and groundwater peaked with agreements signed in the 2000s, or one decade later than agreements and allocation mechanisms overall. The earliest flexible allocation mechanism within the TFDD is in the 1862 *Treaty between Austria and Bavaria Concerning the Regime of the Frontier Line and Other Territorial Relations between Bohemia and Bavaria*, which required consultations between riparians to protect a frontier channel's flows (Article 58). The use of flexible mechanisms to allocate groundwater has grown in popularity over time; this is likely due to the shift in allocation mechanisms towards indirect and principle-based mechanisms, of which several are more flexible in nature than direct mechanisms. However, the data show that the flexible surface water allocation mechanisms included in surface water agreements are more likely to be direct and indirect, rather than principle-based, which parallels the broad trends discussed in the results section.

Much like the allocation mechanisms for environmental purposes, flexible allocation mechanisms are similarly important for locations with high water stress, inter- and intra-annual variability, and drought risk. Table 5 shows the proportion of basins with varying levels of these challenges that have flexible allocation mechanisms according to the TTWA methodology. Surprisingly, basins with high water stress and drought risk have a reduced proportion with flexible mechanisms, yet basins with medium and high levels of inter- and intra-annual variability have more coverage with a flexible allocation mechanism. From the cooperation perspective, this aligns with assumptions of hydro-stationarity: short-term variability is expected, making an agreement easier to reach for flexible mechanisms. Whereas in the long term, relatively consistent discharge is expected, therefore, states are less likely to agree to a flexible mechanism, as planning for meeting domestic needs is more challenging.

Our approach is narrower than the prior assessment by Drieschova *et al.* (2008) in their definitive definition of direct, indirect, and principled allocation mechanisms, as their approach also included clauses that do not directly allocate water resources. For example, they included sharing resources to build infrastructure to make water-sharing more efficient and flexible, or sharing information and technology. These considerations may make agreements and relationships between riparians more robust; however, they do not manage the actual physical division of water between signatories. Through the TTWA, our analysis adds a more focused approach to previous assessments and understandings of how flexibility in physically sharing water has evolved. Further studies based on the accessibility that this paper and the TTWA approach provide on flexibility in water allocation should build on this work by examining the complexity of the flexible allocation mechanisms in international agreements.

CONCLUSION

Allocation has been a primary aspect of transboundary water cooperation, particularly in terms of the academic and policy discourse, as actors have needed to agree on who gets how much water when since the earliest hydraulic civilizations. As such, water quantity and allocation have been a dominant focal point for international freshwater agreements. Despite this, there has been limited scholarship evaluating practical considerations of *how* water is physically shared between states at an international scale and for what purpose. This paper presents a foundation for filling this gap by developing a method for assessing *how* and *why* water is physically allocated. The TTWA is a method for cataloguing and understanding changes over time, space, and design of the mechanisms for water allocation in internationally shared waters. It separates allocation mechanisms into practical and context components, as well as surface water and groundwater allocations.

The analysis presented in this paper identifies several overarching trends in the construction and development of allocation mechanisms, as well as areas for future research. First, there is a generally positive trend, with some fluctuations, such as a peak in the 1990s, in the number of agreements that include allocation mechanisms for surface and groundwater. This is beneficial as the inclusion of allocation mechanisms contributes to the institutional capacity governing these shared resources and potentially adds to the adaptive capacity that will help overcome uncertainties due to climate change and other developments. However, coverage is fragmented, with mechanisms not including all riparian states or only addressing portions of basins, limiting their potential effectiveness in the long term. In addition, the allocation mechanisms themselves are increasing

Table 5 | Proportion of basins within the respective level that have agreements with at least one flexible allocation mechanism.

	Proportion of Basins with Flexible Allocation Mechanisms			
Level or Risk	***Water Stress***	***Drought Risk***	***Interannual Variability***	***Seasonal Variability***
High	20%	50%	47%	71%
Medium	50%	31%	50%	31%
Low	34%	49%	34%	38%

Source: WRI Aqueduct, accessed April 2025.

in flexibility over time by establishing mechanisms that are adaptable to hydrologic change; yet, improvements are needed to address long-term uncertainties due to nonstationary hydrologic realities. Second, most allocation mechanisms do not define a purpose for their allocation, which is, in part, consistent with international water law, particularly the norm of equitable and reasonable use, as it is another means to increase flexibility. For those that do define a context component, *Agriculture/irrigation*, *Hydropower*, and *Domestic use* are the most common; however, *Environmental needs* and *Water quality* are becoming more common since the 1970s. These observations relate to the third overarching trend that a limited number of agreements include allocation mechanisms for environmental purposes. This includes providing minimum flows for environmental needs, establishing a set amount for an environmental flow to maintain ecosystem functions, protecting fishing stocks through allocation for flow, and allocating flow to ensure adequate water quality. Fourth, there has been an evolution in the type of mechanisms included in agreements, moving towards indirect and principle-based practical components and away from direct mechanisms, which may indicate a shift towards more adaptable processes for allocation rather than clearly defined volumetric allocation. In the face of climate change, having a strictly defined allocation could increase the potential for conflict when hydro-stationarity is no longer guaranteed. Lastly, there is an increasing trend in the number of groundwater-specific allocation mechanisms in both groundwater-only and surface water dominant agreements since the 1970s; however, more work is needed to develop groundwater-specific mechanisms that consider the unique characteristics of transboundary groundwater.

The analysis of the state of global practice for transboundary water allocation presented here scratches the surface of the understanding needed to better support the development of allocation mechanisms that are effective at equitably and sustainably sharing water resources. This must be done while being flexible and dynamic enough to meet future challenges and providing the stability needed for economic growth and development. This paper and the development of the TTWA methodology, therefore, present the next step in understanding *how* and *why* water is physically allocated at an international scale. It complements the extensive foundation of knowledge on allocation at the sub-national scale, as well as international water law and the research on negotiating allocation mechanisms for transboundary freshwater agreements. Taken together, this research can better understand the evolving needs for allocation within and between states, as well as support the development of allocation mechanisms that are resilient and adaptable in the face of environmental change.

ACKNOWLEDGEMENTS

This research is a part of the larger ongoing update of the International Freshwater Treaties Database within the TFDD; therefore, we would like to thank all the past and present student research assistants at Oregon State University and The Fletcher School at Tufts University for their hard work and dedication.

FUNDING

The authors would like to acknowledge the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Water Convention), whose secretariat is serviced by the United Nations Economic Commission for Europe (UNECE), and sincerely thank the Water Convention secretariat and UNECE for their support and collaboration on this research. This paper draws from research included in the Handbook on Water Allocation in a Transboundary Context available at: https://unece.org/environment-policy/publications/handbook-water-allocation-transboundary-context. The research is attributed in the Handbook as 'M. McCracken and others, 'Typology of Transboundary Water Allocation: a look at global trends in international freshwater agreements' (forthcoming)'. The findings, interpretations, and conclusions expressed herein are those of the author(s) and do not necessarily reflect the views of the United Nations or its officials or Member States. The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries. In particular, the boundaries shown on the maps do not imply official endorsement or acceptance by the United Nations.

AUTHOR CONTRIBUTIONS

MM contributed to the conceptualization, analysis, writing, and revision. AT and EP contributed to the analysis and writing. SS contributed to the writing and revision. ATW advised and contributed to the revision.

DATA AVAILABILITY STATEMENT

All relevant data are available from https://transboundarywaters.ceoas.oregonstate.edu/international-freshwater-treaties-database.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 23 October 2024; accepted in revised form 23 December 2025. Available online 11 February 2026