Earth System Governance 10 (2021) 100120

Contents lists available at ScienceDirect

Earth System Governance

journal homepage: www.sciencedirect.com/journal/earth-system-governance

An Earth system law perspective on governing social-hydrological systems in the Anthropocene

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A R T I C L E I N F O

Keywords:
Earth system governance
Earth system law
Global hydrologic cycle
Institutional fit
Social-hydrological system

A B S T R A C T

The global hydrological cycle is characterized by complex interdependencies and self-regulating feedbacks that keep water in an ever-evolving state of flux at local, regional, and global levels. Increasingly, the scale of human impacts in the Anthropocene is altering the dynamics of this cycle, which presents additional challenges for water governance. "Earth system law" provides an important approach for addressing gaps in governance that arise from the mismatch between the global hydrological cycle and dispersed regulatory architecture across institutions and geographic regions. In this article, we articulate the potential for Earth system law to account for core hydrological problems that complicate water governance, including delay, redistribution, intertwinements, permanence, and scale. Through merging concepts from Earth system law with existing policy and legal principles, we frame an approach for addressing hydrological problems in the Anthropocene and strengthening institutional fit between established governance systems and the global hydrological cycle. We discuss how such an approach can be applied, and the challenges and implications for governing water as a cycle and complex social-hydrological system, both in research and practice.

1. Introduction

Water governance institutions around the world face mounting challenges as rapid changes in global climate, land use, and socioeconomic and political systems continue to accelerate, resulting in significant alterations to the global hydrological cycle (Lambin et al., 2001; Rockström et al., 2009a,b; Steffen et al., 2015a, b, c, Savenije et al., 2014). Water is the focus of numerous international governance and legal efforts, for example, UN-Water (United Nations, 2021b), UNESCO Intergovernmental Hydrological Programme (UNESCO, 2021), International Network of Basin Organizations (INBO, 2021), the United Nations (UN) Sustainable Development Goals (SDGs) (United Nations, 2021a), Global Water Partnership (GWP, 2000), and the Water Framework Directive in the European Union (EU) (EU, 2000). However, aligning governance and regulatory institutions with the global hydrological cycle remains an elusive and daunting challenge (Moss, 2008; Wierik et al., 2020; Zipper et al., 2020). In this article, we address five features of the global hydrological cycle that pose problems for meeting the ambitious targets of ongoing efforts to reform water governance regimes (Lele et al., 2013): delay, redistribution, intertwinements, permanence, and scale (Falkenmark and Wang-Erlandsson, 2021). While our focus is chiefly on dynamics of the global hydrological cycle, the problems we highlight impact governance institutions at all jurisdictional levels (e.g., local, national, regional).

Governing water not only as a physical resource, in isolation from other Earth systems, but also as a dynamic global cycle, requires

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https://doi.org/10.1016/j.esg.2021.100120
Received 30 June 2021; Received in revised form 26 September 2021; Accepted 25 October 2021
Available online 23 November 2021

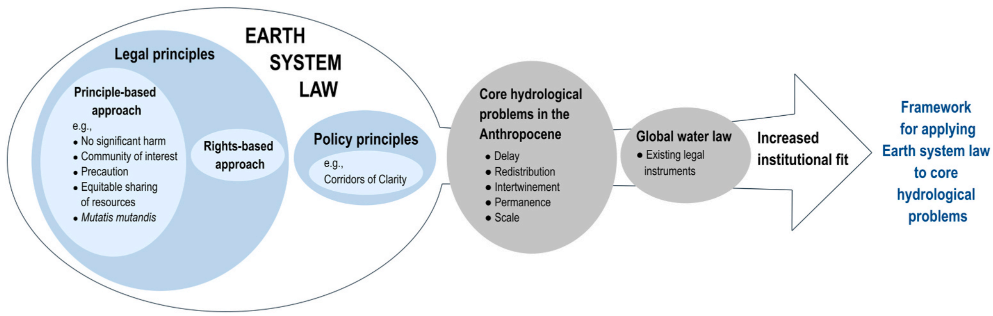

Fig. 1. Approach for applying an Earth system law perspective to core hydrological problems.

addressing the consequences of feedbacks and interactions within and across coupled social-hydrological systems (Pahl-Wostl et al., 2008; Pahl-Wostl, 2009; Boulay et al., 2013; Di Baldassarre et al., 2015). For example, changes in regional land-use patterns driven by human activities are increasingly altering the production and distribution of precipitation globally (Runyan et al., 2012; Pitman et al., 2012; Liu et al., 2013; Lawrence and Vandecar, 2015; Wang-Erlandsson et al., 2018), while these changes in precipitation are in turn driving land-use changes locally (Haddeland et al., 2007; Douglas et al., 2009; Keys et al., 2012). The rapid scaling up of these impacts is a hallmark of the Anthropocene, and reinforces why ongoing water governance reforms must account for, and respond to, intertwinements between social systems and the global hydrological cycle (Keys et al., 2017). Water governance institutions are often aligned with human-defined political and administrative boundaries, yet the dynamics of the global hydrological cycle result in hydrological connectivity across municipalities, countries, and other jurisdictional boundaries (Mancilla García et al., 2019). This problem is one of institutional "mis-fit", or governance structures that do not match the characteristics of the problem(s) at hand (Folke et al., 1998, 2007; Young, 2002, 2008; Galaz et al., 2008).

Scholars and practitioners have long advocated for the re-scaling of water governance institutions to improve "fit", primarily along river basin boundaries (Molle, 2009). The growth of Integrated Water Resources Management (IWRM) in the early 2000s resulted in the proliferation of basin councils and similar decision-making bodies (GWP, 2000), and IWRM remains one of the most widely applied approaches to water resources development internationally (e.g., Cooper, 2021). These decision-making spaces have been essential for ensuring local, Indigenous, and place-based knowledge and values have institutional power (Mancilla García and Bodin, 2019), in spite of mixed success overall (Meijerink and Huitema, 2017). In many cases, this mixed success is due to the problems that governance institutions are required to grapple with – many of which involve global scale social-hydrological dynamics that localities have neither contributed to, nor control – and typically requires cross-level collaboration with other institutions and stakeholders in polycentric governance arrangements (Mancilla García et al., 2019; Lubell and Morrison, 2021). A key challenge to water governance in the Anthropocene is improving institutional fit for addressing the global roots of core hydrological problems, while preserving gains in representation, institutional power, and other successes that have accompanied recent governance reforms.

The recent development of "Earth system law" presents an opportunity for advancing research on institutional fit and governance of social-hydrological systems in the Anthropocene (Biermann, 2007), while integrating an important, but often overlooked, component of governance: legal systems. Earth system law is a legal paradigm that aligns with, and responds to, the Earth system's functional, spatial, and temporal complexities, including physical and societal dynamics, at the planetary scale (Kotzé and Kim, 2019). While no comprehensive and representative juridical framework currently exists that embraces governmentality concerning the Earth system (Lövbrand et al., 2009) – let alone the dynamics of the global hydrological cycle – legal systems are important as they constitute the formal rules that underscore society's rights and obligations, established by public legislative bodies, for shaping behaviors and establishing sanctions for violations through the judiciary (Hart and Green, 2012, p. 3). In this context, the Earth system law paradigm provides a useful set of guidelines for institutional reform that are responsive to the normative, ethical, and regulatory challenges of the Anthropocene (Kotzé and Kim, 2019). As a "legal imaginary" (Kotzé and Kim, 2019; Kim, 2021), Earth system law has the flexibility to incorporate various legal principles, place-based knowledge and practices, and other successful elements of previous institutional reforms.

In this article, we explore how Earth system law can build upon existing legal principles and governance architecture to help address core hydrological problems rooted in Earth system changes (Fig. 1). We further consider how this approach improves institutional alignment between global hydrological realities and laws designed to govern water resources. The remainder of the article is organized as follows: First, we provide an overview of the global hydrological cycle and core hydrological problems to showcase the challenges of governing water in the Anthropocene. We do this to motivate the examination of water law issues from an Earth system law perspective (Section 2). This is followed by examining global water law and governance regimes to outline the (mis)fit between core hydrological problems and current governance architecture (Section 3). We then articulate and apply an Earth system law framing to these social-hydrological problems, with an eye to sources of, and solutions for, institutional (mis)fit (Section 4). Lastly, we conclude and reflect on challenges and considerations for future research (Section 5).

2. Governing the global hydrological cycle in the anthropocene

The global hydrological cycle is characterized by complex interdependencies and self-regulating feedbacks that keep water in a state of constant flux at local, regional, and global levels. These flows drive climatic and biogeochemical processes, supply ecosystems and human industries, and occur over timescales that span seconds to millenia. While water covers around 70% of the Earth's surface, freshwater resources – the primary focus of this article – account for less than 3% of all water found on Earth (Lubchenco and Petes, 2010). These freshwater resources include "blue" (visible) water present in lakes, rivers, aquifers, snow and ice, and the atmosphere, and "green" (invisible) water contained in soil and vegetation (Falkenmark et al., 2019). Human activities are increasingly altering the distribution of blue and green water resources both directly, through activities such as water extraction and wastewater management, and indirectly, through land-use change and fossil fuel consumption (Haddeland et al., 2014; Wang-Erlandsson et al., 2018; Douville et al., 2021).

The need to understand and maintain the hydrological cycle's critical role for a resilient Earth system, and society's contributions to changes in the cycle, is as challenging as it is urgent in the Anthropocene (Falkenmark et al., 2019; Gleeson et al., 2020). Numerous efforts have been made to define, measure, and monitor the state of global freshwater resources and their contributions to the biosphere (e.g., Falkenmark, 1989; Gordon et al., 2005; Vörösmarty et al., 2010; Gleeson et al., 2012; Brauman et al., 2016; Kummu et al., 2016). One of the most widely recognized efforts is the "freshwater use" boundary in the planetary boundaries framework (Rockström et al., 2009a, b; Steffen et al., 2015a, b, c). This "boundary" comprises a global upper bound to human consumptive use of blue water and regional lower bounds of streamflows, beyond which changes in the global hydrological cycle increasingly risk pushing the Earth system away from the conditions of the Holocene that support modern agriculture-based civilizations (Rockström et al., 2009a, b; Steffen et al., 2015c). Gleeson et al. (2020) further expanded on this research by highlighting a need to more explicitly and comprehensively represent the role of the entire water cycle – soil moisture, atmospheric water, frozen water, surface water, and groundwater – for supporting Earth system functioning.

While the planetary boundaries framework and other related efforts are premised on maintaining conditions for a habitable biosphere, downscaling global metrics for actionable targets at the local, national, and regional levels is exceedingly difficult (Dearing et al., 2014; Zipper et al., 2020; Bunsen et al., 2021). Water availability is the starting point for most water governance decision-making processes at the local and regional levels (McCaffrey, 2014, 2019). Yet, water availability is increasingly variable and uncertain due to accelerating climate- and land system-induced changes in the global hydrological cycle (e.g., Immerzeel et al., 2010; Gudmundsson et al., 2017; Greve et al., 2018; Levia et al., 2020). For example, atmospheric water plays a role in regulating Earth's climate and in driving local and regional precipitation patterns, while changes in atmospheric water are the result of complex global dynamics that are increasingly driven by human activities (e.g., Keys et al., 2017; Staal et al., 2018 Wang-Erlandsson et al., 2018). Therefore, governance solutions to water scarcity, declining water quality, and related challenges of water distribution and access must necessarily account for the multi-level interconnectedness of hydrological flows across spatio-temporal and institutional scales (Müller et al., 2006).

At the heart of these issues lies the need to govern water in the Anthropocene as a dynamic global cycle and co-evolving social-hydrological system (Sivapalan et al., 2012, p. 1275; Rockström et al., 2014). This includes recognizing changing societal norms and values, as well as different system behaviors and feedback mechanisms that can result in exceeding tipping points beyond which a change or effect cannot be easily reversed (i.e., hysteresis) (Lenton et al., 2008; Di Baldassarre et al., 2013; Thompson et al., 2013). For example, climate change and deforestation are currently jointly propelling the Amazon rainforest into a vicious cycle of rainfall reductions, drought, fire, forest loss, and further losses in regional water cycling (Staal et al., 2020). A large-scale forest dieback will have severe repercussions from the local to global scales, negatively impacting regional agricultural production and water resources, but also global climate and atmospheric circulation (Lawrence and Vandecar, 2015). How the fate of the Amazon forest will play out is ultimately a result of the complex interplay between social-hydrological processes occurring across space and time, and involving international trade, national and international politics, evolving social norms, and Anthropocene surprises such as the recent COVID-19 pandemic (Daly, 2020), among others. Furthermore, feedback mechanisms may be emergent due to non-linear interactions between processes occurring at different spatio-temporal scales (Blair and Buytaert, 2016; Schlüter et al., 2019).

While there has been a growing interest among legal scholars to engage with resilience concepts (e.g., Ebbesson and Hey, 2013; Arnold and Gunderson, 2013; Bohman, 2021) and in studies of water governance (Garmestani and Allen, 2014; Cosens and Gunderson, 2018, 2021), this has not always resulted in direct engagement with research from the physical sciences, which is necessary for understanding the functioning of the global hydrological cycle. The Earth system law paradigm provides an important perspective for reconciling complex social-hydrological governance challenges in the Anthropocene. As an "innovative legal imaginary that is rooted in the Anthropocene's planetary context and its perceived socio-ecological crisis" (Kim and Kotzé, 2020, p. 11), Earth system law allows for creativity in the pursuit of opportunities for connecting dynamics of the global hydrological cycle with governance solutions at local, national, and regional levels. The reason is that Earth system law embraces transdisciplinary systems thinking, which serves as the basis for regulatory analysis (Kotzé and Kim, 2019). This stands in stark contrast to the tradition of reductionism within legal research (e.g., Aragão, 2016; Bosselmann, 2016).

The Earth system law paradigm further addresses problems from a multi-level perspective, embraces polycentric order, and fundamentally challenges traditional perceptions of the role of law and law's many actors, processes, and operative domains (Kotzé and Kim, 2019). Importantly, Earth system law does not imply one overarching global institution for governing water, nor does it usurp or otherwise undermine local and place-based laws and norms of governance. Rather, it represents a perspective that can be incorporated into, and in support of, existing institutions to better inform decision-making at all levels of governance. Identifying avenues for how this can be accomplished, in the case of social-hydrological systems, is at the heart of this article.

2.1. *The global hydrological cycle as a challenge to institutional fit*

Numerous laws and regulations exist for governing components of the global hydrological cycle, but we do not presently have any governance institutions that address the cycle as a coherent whole. The result is a highly fragmented approach to water governance (Gupta et al., 2013; Kim et al., 2015), where rules and allocations are typically based on water availability for specific end-uses within a given jurisdiction. In contrast, a holistic cycle-based approach would account for external sources of variation in water availability and the dynamics driving these variations (e.g., Keys et al., 2017). However, this can often only be accomplished indirectly, through coordination and communication with other actors and governance institutions in interconnected hydro-social territories (Mancilla García et al., 2019), and typically occurs on an ad-hoc basis.

The evolution of IWRM thinking in recent decades has facilitated the adoption of approaches to water governance that account for the interconnections between human society and aspects of the hydrological cycle, and the need for integrated responses based on resilience thinking (Cooper, 2021). IWRM further recognizes that governing water resources effectively requires addressing land use and related resources, and balancing social and economic wellbeing with ecosystem health (GWP, 2000). Much effort has been invested in IWRM and the creation of governance institutions that follow surface water boundaries (Mollinga et al., 2007; Molle, 2009; Conca, 2005), however, IWRM is not a panacea (Cohen and Davidson, 2011; Cooper, 2021; Hileman et al., 2016). In spite of important successes, basin councils are still not equipped to govern the whole of the hydrological cycle, the dynamics of which are largely responsible for the amount of available water in a given basin – the basis for planning and decision-making processes.

Overall, existing water governance institutions display varying degrees of institutional (mis)fit, and none possess all the legal and regulatory architecture necessary for governing dynamics of the hydrological cycle at all relevant scales. "The problem of fit asserts that the effectiveness and the robustness of social institutions are functions of the fit between the institutions themselves and the biophysical and social domains in which they operate" (Folke et al., 2007, p. 2 (adapted from Young and Underdal, 1997)). In the context of social-hydrological systems, institutional fit arises when the boundaries of the governance system align with the characteristics of the relevant hydrological problems. However, legislative instruments do not presently account for the complex and multi-level interconnectedness of the global hydrological cycle, which is the root of many pressing social-hydrological problems at

Table 1
Core hydrological problems in the Anthropocene adapted from Falkenmark and Wang-Erlandsson (2021, p. 217).

Hydrological Problem	Defining Characteristics and System Dynamics	Real-world example	Social impacts
Delay	The effects of changes in hydrological systems can be **delayed** due to (a) an erosion of system resilience and (b) a slow system response. This means that the cumulative effects of changes might become evident only in the case of additional disturbances.	**Forest resilience** Forest resilience loss in the Amazon may not be manifested as forest loss until the occurrence of an external disturbance such as a drought (Staal et al., 2015).	Impacts manifest beyond the time-scale of election cycles, or even human time scales, which demand unconventionally long-term considerations in governance.
Redistribution	Spatial and temporal **redistribution** of water resources may occur due to water-function perturbations of different components of the hydrological cycle, for example, loss of water infiltration into the soil from a previously vegetated area. This reduces the amount of water available for transpiration (i.e., the loss of water through leaves that accompanies plant growth), and can create dynamics that accelerate the loss of water resources from a locality or region.	**Drought associated with changes in transpiration** Since transpiration can travel longer distances in the atmosphere during dry weather than rainy weather (Wang-Erlandsson et al., 2014; van der Ent et al., 2014), long-distance rainfall recycling can be affected by local changes in water flow phenomenon and sub-flows.	Previous management solutions become useless due to new system dynamics.
Intertwinements	Water cycle dynamics as inherently **intertwined** with other parts of complex social-ecological systems that can also result in surprising synergies, cascades, and teleconnections.	**Deforestation and climate change-related drought** The fate of the Amazon is linked to a complex interplay of regional water cycles, agriculture, national-to-global politics, economics, international trade, atmospheric circulation, global climate, etc. (Lawrence and Vandecar, 2015; Daly, 2020).	Difficult to model and predict where and when effects will emerge.
Permanence	Water partitioning modifications caused by, for example, loss of infiltration capacity in soils due to land degradation may result in consequences in varying degrees of **permanence** on account of system hysteresis and cost and feasibility of ecological restoration.	**Soil erosion** Soil erosion impacts water partitioning and water functions that have a relatively high permanence. This is problematic since the timeline for soil regeneration is very long (i.e., decades to centuries). This is evident concerning ecological succession for soil restoration (Jiao et al., 2007; Rossi et al., 2017).	Transformation of the system results in unprecedented adaptation to new system features.
Scale	Multiple, diverse, and interrelated perturbations of green and blue water functions could degrade and destabilise hydrological systems at multiple **scales**.	**Dam construction** The construction of dams and reservoirs impact regional river fragmentation and results in flow disturbance for wider aquatic ecosystems (Choudhary et al., 2012; Grill et al., 2019) and alteration of surrounding vegetation and hydroclimatic conditions (Sun et al., 2021; Thieme et al., 2021).	Unintended effects in systems in other jurisdictions.

the local and regional levels (Falkenmark and Wang-Erlandsson, 2021). Abbott et al. (2019a) argue that this lack of considerations to date is due to a lack of understanding of the functioning of Earth systems in society and how these functions relate to human wellbeing, and call specifically on lawyers and policymakers to consider the functioning of the global hydrological cycle (Abbott et al., 2019b; Attari, 2014; Linton, 2014).

Ultimately, no single institution is capable of regulating the whole of the hydrological cycle. Cross-level collaboration is often needed to treat root causes – not merely symptoms – of water resource problems (Mancilla García et al., 2019), although empirical research has shown this does not always happen even when actors are aware of such interdependencies (Hedlund et al., 2021). This becomes especially problematic at the global level; numerous international institutions exist, but none are truly global in scope. Therefore, an analysis that acknowledges polycentric order, i.e., “many centres of decision making that are formally independent of each other” (Ostrom et al., 1961, p. 831), can reveal important information about fragmented governance systems and suggest ways of improving coordination. This approach also enables a better understanding of how certain values and norms inform the law, and can help capture the law’s interaction with other important forms of constraint – such as social norms – observed through patterns of coordination and cooperation between different stakeholder groups.

2.2. *Core features of hydrological problems in the anthropocene*

Table 1 outlines five hydrological problems proposed by Falkenmark and Wang-Erlandsson (2021) as core features of social-hydrological systems in the Anthropocene. These features represent the current state of knowledge in the field, and capture essential functions of the hydrological cycle for supporting, regulating, and stabilizing social-hydrological systems. We provide real-world examples of each problem as an illustrative case, and note there are many other examples of these phenomena. We also note that while the dynamics and impacts may be perceived as local, they are not in reality – “in the Anthropocene, nothing is solely local” (Falkenmark and Wang-Erlandsson, 2021, p. 218). For example, the construction of dams and reservoirs can often be connected to habitat fragmentation and to methane emissions from eutrophication, while the aggregated effects of these impacts on biodiversity and climate can extend to regional and global levels (Deemer et al., 2016).

3. Architectures of global water law and governance

We use the term “global water law” here to reflect our focus on institutions that transcend state-based international water law and encompass regional and international state and non-state law. This terminology is motived by the fact that hundreds of bilateral and global water framework treaties and directives presently exist (Dellapenna, 1994; Dellapenna and Gupta, 2008), and that significant contributions have been made in mapping and articulating what global water law is today (Dellapenna et al., 2013). Numerous international water governance institutions have been established through these efforts and are well documented in the literature (e.g., McCaffrey, 2001; Conca, 2005; Malla, 2005; Dellapenna and Gupta, 2008; Pahl-Wostl et al., 2008;

Dellapenna et al., 2013; Keys et al., 2017). These include formal institutions created under the auspices of the UN and other international organizations, and bilateral and multilateral treaties (see Dellapenna, 1994; UNEP, 2019).

The following section presents a handful of the main legal principles and instruments (e.g., conventions, treaties) that collectively form the cornerstones of global water law. These instruments are fragmented and limited in their functional and geographical coverage, and address only some elements of the global hydrological cycle. Nevertheless, they are among the most important elements of governance architecture (Biermann and Kim, 2020) and serve as the entry point for our consideration of hydrological problems in the Anthropocene, and for discussion of how governance of social-hydrological systems can be improved through incorporating an Earth system law perspective.

3.1. Existing instruments of global water law

In Table 2, we present a selection of major instruments of global water law to showcase their scope, scale, and primary focus. This overview is neither intended to provide a complete list, nor provide analytical and explanatory evidence. Instead, the prupose of this table is to provide a descriptive outline of cornerstone instruments in global water law.

Two major international conventions for transboundary water cooperation are the UN Convention on the Law of Non-Navigational Uses of International Watercourses (UN Watercourses Convention) (United Nations, 1997), and the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (the Water Convention) (UNECE, 1992). The UN Watercourses Convention is a framework treaty with many proponents (e.g., Salman, 2007; Rieu-Clarke, 2011) and entered into force in 2014 (UNECE, 2021a). The Water Convention is both an international framework instrument and an intergovernmental platform that aims to ensure the sustainable use of transboundary water resources by facilitating cooperation. Initially negotiated as a regional instrument, it was opened up for accession to all UN Member States in 2016. The Protocol on Water and Health is another important international instrument. This is an instrument adopted "specifically to attain an adequate supply of safe drinking water and adequate sanitation for everyone, and effectively protect water used as a source of drinking water" (UNECE, 1999).

While not a global instrument, per se, the EU Water Framework Directive (WFD) is recognized as one of the most ambitious legal instruments in the field of water law and policy internationally. The overall aim of the WFD is to achieve a good status of all surface and groundwater resources in the EU (Albrecht, 2013), however, there have been many different challenges with its implementation. For example, the goal of achieving "good" water quality has proven to be too vague, and there has been insufficient data available documenting the member states' water resources throughout the years (e.g., Henriques et al., 2015; Brack et al., 2015). The WFD outlines a detailed framework for monitoring, planning, and acting to achieve healthy waters for ecosystems and human consumptive uses. As such, the WFD institutionalizes ecosystem-based objectives and planning processes at the basin level as the unit for management and decision-making (Kallis and Butler, 2001;

Table 2
A selection of major instruments of global water law.[a]

Legal instrument	Scope and scale	Primary focus
UN Watercourses Convention and the Convention on the Protection and Use of Transboundary Watercourses and International Lakes	International and global framework instrument, i.e., it does not replace bilateral and multilateral agreements for specific basins or aquifers (UNECE, 2021b).	The Water Convention focuses on the prevention, control and reduction of transboundary impact; using transboundary waters in a reasonable and equitable way, and ensuring their sustainable management (UNECE, 2021b). The Convention uses a thematic assessment based on the so-called "water-food-energy-ecosystems nexus" in river basins. This approach refers to these sectors being inextricably linked, meaning that actions in one policy area commonly impact others, including ecosystems that humans ultimately depend upon (UNECE, 2021c).
UN Convention on the Law of Non-Navigational Uses of International Watercourses	A framework convention governing international watercourses (United Nations, 2021b).	The Watercourses Convention constitutes a global legal mechanism for facilitating the equitable and sustainable management of transboundary rivers, lakes, and groundwater aquifers worldwide (United Nations, 2021b).
International Law Association's Berlin Rules on Water Resources	The Berlin Rules include within their scope both national and international waters to the extent that customary international law speaks to such waters (ILA, 2004). The Berlin Rules cover all freshwater and related resources (including characteristics of groundwater) and integrate domestic and international water law (Dellapenna, 2006; Dellapenna and Gupta, 2008).	The Berlin Rules focus on environmental concerns, integrated management, and sustainable development as central principles of international environmental law.
The Protocol on Water and Health	International and global framework instrument.	The main aim of the Protocol is to protect human health and well-being through good water management. This means to protect aquatic ecosystems and by preventing, controlling, and reducing water-related diseases. The Protocol is adopted specifically to achieve safe drinking water and adequate sanitation (UNECE, 2021d).
Convention on wetlands of international importance especially as waterfowl habitat	International and regional framework instrument.	It is required that parties of the Convention should be informed (at the earliest possible time) about the ecological character of any wetland in its territory and included in the List of Wetlands of International Importance (United Nations, 1971). Central for the Convention is the concept of "ecological character", which has been left vaguely defined (Bridgewater et al., 2014; Bridgewater and Kim, 2021), including after the conceptual update by the Millenium Ecosystem Assessment (2005).
Directive 2000/60/EC of the European Parliament and of the Council of October 23, 2000 establishing a framework for Community action in the field of water policy	A European framework instrument	The purpose of the WFD is to establish a framework for protecting inland surface waters, transitional waters, coastal waters and groundwater (EU, 2000).

[a] For a complete list of legal water instruments, see the International Environmental Agreements (IEA) Database Project (Mitchell, 2020).

Nilsson et al., 2004).

Scholars have demonstrated that the WFD has contributed to new thinking around water governance and inspired other models (van Rijswick et al., 2021), which has led to concentrated efforts to export and scale out the concept of the WFD in different forms, including the EU Water Initiative. The WFD has, at the same time, instigated political resistance and bureaucratic fatigue, in addition to the limited positive impact on the aquatic environment (Moss et al., 2020; Fritsch et al., 2020). However, while the flexible governance design of the WFD created high expectations, it has not been as successful as many had hoped for. The design has resulted in noncompliance and loopholes, which has made it fairly ineffective in several countries (e.g., Liefferink et al., 2011; Salmaso et al., 2012; Koontz and Newig, 2014).

Another important aspect of global water governance today is that of soft law. Even though it is not binding law, the 2030 Agenda for Sustainable Development is a key instrument guiding governance aspirations for 2030 (Kim, 2016; Biermann et al., 2017; French and Kotzé, 2018). SDG 6 is a key instrument (McIntyre, 2018) that aims to "ensure availability and sustainable management of water and sanitation for all" (United Nations, 2021a), while SDG 16 aims to "promote peaceful and inclusive societies" (United Nations, 2021a).[2] These have further provided both direct and indirect support to efforts for managing transboundary water resources. Several additional SDGs have direct or indirect effects on components of the global hydrological cycle. For example, SDG 13 suggests to "take urgent action to combat climate change and its impacts" (United Nations, 2021a); SDG 14 suggests to "conserve and sustainably use the oceans, seas and marine resources for sustainable development" (United Nations, 2021a); and SDG 15 suggests to "protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation and halt biodiversity loss" (United Nations, 2021a). It is well established that there are many interactions and synergies among the SDGs (Weitz et al., 2018; Pedercini et al., 2019), which has been shown in the context of water quality and water resources such as wetlands (Alcamo, 2019; Bhaduri et al., 2016; Gain et al., 2016; Jaramillo et al., 2019), indicating that this collection of soft law instruments might have a greater effect on preserving desirable cycle dynamics than more formal instruments that address only single issues or components of the hydrological cycle.

Underlying all of these existing instruments of global water law are various legal principles. In international law, principles can promote coherence and consistency as they provide a guiding framework for its implementation (e.g., Birnie et al., 2009; Sands and Peel, 2012). Sánchez Castillo (2020) argues that a principle-based approach could serve as the foundation for the sustainable governance of shared resources. Generally, there are two substantive principles in global water law. First, the principle of "equitable and reasonable utilization" could be seen as a softer version of the doctrine of absolute sovereign territory. This principle holds that a State has absolute rights to all water flowing through its territory. The second principle is "no significant harm" and requires – in the UN Watercourses Convention – that States, "in utilizing an international watercourse in their territories, take all appropriate measures to prevent the causing of significant harm to other watercourse States" (United Nations, 1997). This principle could be applied as absolute riparian integrity (a state is entitled to the natural flow of a river system crossing its borders), including historic rights where every riparian state is entitled to water tied to a prior or existing use (Wolf, 1999). Using principles of international law could facilitate effective transboundary water resources management involving riparian countries with shared watercourses (e.g., Rahaman, 2009).

[1] The SDGs are supplemented by earlier initiatives under the auspices of the UN, where the recognition of a human right to water and sanitation is key (United Nations, 2010).

3.2. Social-hydrological systems and institutional fit

The broad institutional literature highlights how different institutional arrangements provide different governance functions, and that different functions may be required for different problems (e.g., Young, 2010). Using an integrated governance approach that recognizes multiple decision-making centres for shared water resources, from the local level to the transnational, complicates the challenges to be navigated as different institutions carry out their administrative competencies (e.g., Mancilla García et al., 2019). Nevertheless, these kinds of analyses have a general relevance in that they can help to evaluate governance surrounding any emerging environmental threat as a first step to guiding the development of jurisdictionally realistic solutions (Ekstrom and Crona, 2017). Therefore, considerations of institutional fit also have a role in determining whether global water law and its regulation properly interprets and considers environmental factors that water resources are affected by, or affect, in different ways across social-hydrological systems.

Current governance architecture only accounts for some of the global hydrological cycle dynamics, e.g., through the focus on transboundary, ecosystem, and nexus concerns (see Table 2). One notable gap is that global water law – including the UN Watercourses Convention, the Water Convention, and the 2008 Law of Transboundary Aquifers (United Nations, 2008) – mainly target blue water, not green water. This is problematic as the majority of global water flows through ecosystems, and human appropriation, are green water flows (Haddeland et al., 2011; Hoff et al., 2010; Hoekstra and Mekonnen, 2012). Human consumption of green water is over three times as large as that of blue water (Hoff et al., 2010). Over 30% of terrestrial precipitation is also used to sustain natural vegetation that provides ecosystem services to society (Rockström et al., 2014). Moreover, green water resources are limited, and their scarcity is often overlooked (Schyns et al., 2019). At the same time, it is neither feasible nor desirable to establish governance instruments that target either blue or green water flows at a global scale. The consequences of hydrological problems are primarily manifested at local and regional levels, which are also the levels at which most water governance institutions operate. Whether or not these institutions are effective, it is necessary to work within existing governance architecture as human institutions will always, to a greater or lesser extent, be defined along human-defined political and administrative boundaries.

If it is neither feasible nor desirable to enact a comprehensive global convention or treaty for governing the global hydrological cycle, how can current governance and regulatory architecture be reformed to address important cycle functions? We argue that Earth system law provides a helpful framing that can guide solutions to core hydrological problems by accounting for interconnections among the elements of the hydrological cycle and imbalances among administrative units. In the next section, we use the core hydrological problems posited by (Falkenmark and Wang-Erlandsson, 2021, p. 217) to elaborate on this thinking.

4. An earth system law perspective on social-hydrological systems

The social-hydrological problems discussed above provide a concrete focus for structuring discussion around the role Earth system law can play for improving governance of hydrological cycle functions. Significant sources of uncertainty are embedded within social-hydrological systems (e.g., annual and seasonal variations in precipitation, locations of evaporative sources contributing to precipitation), and which are being further exacerbated by the scale of human activities in the Anthropocene. Earth system law provides a valuable framing for addressing uncertainty that recognizes the multi-level and interconnected characteristics of hydrological flows and the polycentric governance structures that have evolved to manage water resources at multiple scales. Nevertheless, the key challenge moving forward is translating Earth system law from a conceptual construct to a guide (see Kotzé, 2020) for informing improved governance of social-hydrological systems in practice.

4.1. A principle- and rights-based approach to Earth system law

A clear entry point for applying Earth system law to improve regulation of social-hydrological systems, which are increasingly influenced by alterations in complex global hydrological processes, is through a principle-based approach. With this approach, we mean to enhance the role of legal principles further, considering the significance and inherent role that legal principles have played in global water law. For example, this is illustrated through the adoption of the Berlin rules (ILA, 2004; Dellapenna, 2006), and through the establishment of the UN Rio Declaration on Environment and Development (Viñuales, 2015). With this focus, we do not argue against the significance of legal doctrine. Instead, through adopting an interdisciplinary perspective, and by making use of insights from the literature on institutional (mis)fit, we introduce the value of applying and combining legal principles. However, even using the perspective of institutional fit is unlikely to create "perfect" solutions, given the dynamic nature of social and ecological problems (see Armitage et al., 2008). Often, the focus is on a narrow range of attributes when analyzing congruence between institutional and biophysical systems. Moreover, the aspect of congruence is only one of the many ways institutions can fit social and ecological contexts, and it is not evident that it can result in simple and intuitive measures (Epstein et al., 2015).

Moreover, law can often create resistance to flexible changes in social-ecological systems (Bohman, 2021). In this context, we argue that legal principles can provide for the flexibility that is needed for legal decision-making, considering the complexity and uncertainty of the Anthropocene. Additional arguments for an evolving interpretation of principles of international environmental law can be found in Sands et al. (2018). This notion of flexibility can be compared to institutional flexibility; a formal mandate for adaptive management[2] for adaptive institutional design, including adaptive leadership, which can push against existing institutional bounds and generate surprises. Ideally, this should further enable and foster participation through incorporating different stakeholder perspectives, manage conflict, and facilitate social learning (e.g., Peat et al., 2017). In addition to the principles of equitable utilization and no significant harm previously discussed, other relevant legal principles exist in global water law that bear mentioning in our consideration of Earth system law here. These include the principles of "permanent sovereignty over natural resources", "the community of interests", "common concern of humankind", "public participation", and "sustainable development". Together, these principles offer a general, yet integrated, guide for equitable utilization and environmental protection of shared resources (Sánchez Castillo, 2020). However, these principles alone do not fully address the complexity and uncertainty that characterizes social-hydrological dynamics in the Anthropocene (Crutzen and Stoermer, 2000; Waters et al., 2016), but they do contribute to the identification of pathways for guiding application of the law.

The principle of no significant harm implies that decisions should not be taken that can result in direct or indirect negative consequences (e.g., deteriorating water quality, unsustainable withdrawals from surface or groundwater sources), which is a challenge when dealing with uncertainty and complex system dynamics. Policymakers frequently argue that more accurate model predictions are needed to aid in water governance decision-making. Yet, the calls for more data have become a source of leverage and contestation in political negotiations. More data also does not necessarily equate to transparency and accountability (Moore et al., 2018), nor does it always succeed in reducing uncertainties around water availability, tipping points, and other important hydrological phenomena (e.g., Carpenter et al., 1999; Mäler et al., 2003; Crépin, 2007; Keys et al., 2019).

The principle of community of interests refers to a "legal recognition of the unity of the drainage basin and promotes riparian solidarity and cooperation as well as the formation of a community of law" (Sánchez Castillo, 2020, p. 156). Hydrological flows across local, regional, and global scales have important implications for responsibility and liability and pose challenges to developing effective legal institutions and multi-actor cooperation (Ebbesson, 2010; Ebbesson and Folke, 2014). The complex issues that characterize social-hydrological systems must be identified and addressed by multiple public and private interest groups. However, actors may hold different opinions regarding the severity of problems, the suite of potential solutions, and timeframes for action. This is further exacerbated by uncertainty in the form of fragmented and potentially conflicting information and scientific data, which can serve as a barrier to action (see Galaz, 2014).

Access to water is now recognized as an international human right, and both the United Nations General Assembly and the Human Rights Council adopted resolutions on the topic in 2010 (United Nations, 2010; HRC, 2010). There has also been a shift in international law – where water previously was considered an issue of states' mutual rights and duties – states' general water governance and management duties, including domestic water allocation are now considered (Hey, 2009). This is reflected in the 1999 Protocol on Water and Health to the Water Convention (UNECE, 1999), listed in Table 2. In one of the earliest attempts to reflect on the water boundary from the planetary boundaries framework, Ebbesson (2014) noted that the starting point for a discussion on water quantity could be a minimum level of a human right to water. However, there are criticisms of the usefulness of a rights-based approach. For example, the primacy conferred to rights, rather than responsibilities within legal systems and within the discipline itself, may be part of the problem and enable breaches of planetary boundaries, according to Frisso and Krik (2021). Additionally, the World Health Organization already specifies 50 L per person per day as the minimum level of necessity (WHO, 2017). However, the recent experiences with "Day Zero" in Cape Town, South Africa highlights how difficult it is in reality to maintain basic levels of sanitation (Enqvist et al., 2020). As such, it may be necessary to supplement the rights perspective with additional tools.

The precautionary principle refers to preventative decision-making in the face of risk and considerable uncertainty (e.g., Harremoës et al., 2001; de Sadeleer, 2007; Garnett and Parsons, 2017). This is challenging given the behavior and vulnerabilities of complex social-hydrological systems, and the multiple ethical and political dimensions that accompany such decisions (Galaz, 2019). Yet, improving governance of social-hydrological systems requires deep understanding of system dynamics (Ostrom, 2007). For example, current legal institutions do not address key aspects of the global hydrological cycle, including precipitationsheds and moisture recycling (Keys et al., 2017). Keys et al. (2017, p. 19) argue that "it should be possible to apply established principles, e.g., on 'no harm' and on 'equitable and reasonable utilization of resources', *mutatis mutandis*, in situations where activities cause transboundary changes of evaporation sources and precipitation sinks". The principle *mutatis mutandis* means "taking into consideration or allowing for the changes that must be made" (e.g., Adams, 1961, p. 160), while the principle of equitable and reasonable utilization of resources entails that every water user has a right and should have a reasonable and equitable share in the water resources within their area of jurisdiction (Wohlwend, 2001).

In the case of transboundary changes, Keys et al. (2017) maintain that "no harm" should mean that "one should use one's own property so as not to injure another" (Bratspies and Miller, 2006). It is also important to define what "equitable and reasonable utilization" would then mean for the allocation of finite resources and that access should be based on

[2] Adaptive management is flexible community based management tailored to specific places and situations and supported by, and working with, various organizations at different levels (Olsson et al., 2004).

principles of equity (Keys et al., 2017). The reason is that no significant harm also means not creating injustice; when the activities of one powerful actor are degrading water quality, this causes harm and marginalization to others residing downstream in the watershed. Interestingly, the no-harm principle works well in instances of transboundary harm on rivers as it qualifies sovereignty. However, while the adoption of Agenda 2030 aim in essence to reduce harm, the 'no significant harm' principle is not mentioned at all. At the same time, the agenda do promote full permanent sovereignty over natural resources (Gupta and Schmeier, 2020). Moreover, the no-harm principle is further complemented by the precautionary principle (Gupta and Schmeier, 2020), which in turn is qualified through cost-effectiveness meaning that lack of scientific certainty should not postpone cost-effective measures (United Nations, 1992). This translates to an even weaker position of the no-harm principle in international environmental law. Gupta and Schmeier (2020) even suggest that the no-harm principle will become ineffective if it cannot question economic policies whose primary focus is on growth.

Considering the need for new legal thinking in the Anthropocene and our focus on Earth system law, we argue it is not only necessary to develop flexible institutions and regulation, but even what could be considered flexible principles. Polasky et al. (2020) suggest four principles (not to be confused with the previously discussed legal principles) that can be applied to create more effective governance responses in the face of uncertainty, which often prevents timely and appropriate decision-making. These principles are: a) "follow the most robust and most direct path between policy decisions on outcomes"; b) "focus on finding sufficient evidence for policy purpose"; c) "prioritize no-regrets policies by avoiding options with controversial, uncertain, or immeasurable benefits"; and d) "aim for getting the big picture roughly right rather than focusing on details" (Polasky et al., 2020, p.1). Polasky et al. (2020) describe this approach as "identifying corridors of clarity." This refers to the creation of a sufficient level of understanding of critical phenomena or causal pathways to justify taking policy action in a particular direction. This is a critical difference compared to other evidence-based decision-making processes, which have proven unreliable due to increased complexity and uncertainty. At the same time, while flexibility and principle-led governance are necessary when establishing legal solutions for more than one country, a similar approach to flexibility could be one of the reasons why internationally ratified treaties still are not properly followed even if implemented (e.g., UN treaties). Thus, there is an inherent tension between the need for flexibility and a degree of rigidity in law.

4.2. A framework for applying Earth system law to core hydrological problems

Drawing on the principle-based approach outlined above, we propose a simple framework for guiding the application of Earth system law (Table 3) to address the features of core hydrological problems in the Anthropocene (Kotzé and Kim, 2019; Kim and Kotzé, 2020). Again, considering the need for increased flexibility for legal decision-making due to complexity and uncertainty, we introduce a dynamic and enhanced role of legal principles. In line with Viñuales (2015), we also make note of the relations between principles, but from an Earth system law perspective. As captured in Table 3, the use of legal principles could be arranged to increase institutional fit through addressing "cross-spatial" (redistribution, scale, intertwinements), "cross-temporal" (delay and permanence), and/or "cross-sectoral" (redistribution, scale, intertwinements) dynamics of the global hydrological cycle.

Hydrological *delay* can arise when erosion of system resilience becomes evident (see, e.g., Van Nes and Scheffer, 2007), as in the case of disturbance or when system response is slow. For example, short-term decisions in lake restoration that prioritize increasing the quantity of water available for consumptive uses could have long-term consequences for water quality. Over time, even small changes can result in ecosystem decline and lead to tipping points (Martin et al., 2020). Delays in system responses also increase the level of uncertainty, resulting in a false sense of security when the system appears to be fine at present, while in reality, the effects of the disturbance will manifest themselves later (Hughes et al., 2013).

In such highly complex situations, the precautionary principle is an important legal principle for guiding decision-making. The precautionary principle emphasizes thorough review before taking actions to assess the benefits and consequences of potential interventions to the system and typically results in at least temporary non-action. Therefore, it is useful to use the flexible policy principles by Polasky et al. (2020), and notably, policy strategy (b), which focuses on finding sufficient evidence for policy purposes. In this way, there might be a faster transition from inaction to action. However, it is important to note that there is a risk for exploiting current states of evidence (or lack thereof), and this principle should be used together with a rigorous risk assessment. At the overarching governance level, we maintain that scenario planning may be useful as there is a significant need to foresee harm instead of only addressing it ex post facto (unless the impacts are unknown, and in that case it does not apply) (see Kim and Kotzé, 2020).

Hydrological *redistribution* describes how perturbations in the hydrological cycle often result in spatial and temporal changes to water availability, which means that existing governance structures may require considerable changes to adjust to new system dynamics (Falkenmark and Wang-Erlandsson, 2021). For example, when perturbations result in diminished rainfall within a watershed, acute water scarcity can result if conservation efforts do not reduce consumption. In this situation, the human right to water (United Nations, 2010) should be acknowledged when discussing water quantity (Ebbesson, 2014). This becomes even more important in the case of redistribution, where previous access to water may have been deprived and must be upheld somehow, which is possible if explicitly recognizing the importance of the right to water. Through an implemented right to water, these sudden changes may be managed if the spatial and temporal aspects of access to water are redistributed back to people who had access (and are in great need of access). This may still be a significant challenge in practice; however, we argue that if (1) implementing the human right to water, and in order to operationalize the right, (2) support will be needed from the principle of equitable and reasonable utilization of resources. Chiefly, this phenomenon most likely creates new dynamics between different actors at the local level, and also possibly between jurisdictions.

However, interpreting the right to water, and equitable and reasonable utilization of resources, from an anthropogenic standpoint

Table 3
Framework for applying Earth system law to core hydrological problems (adapted from Falkenmark and Wang-Erlandsson (2021, p. 217).

	Precautionary principle	Human right to water	Equitable and Reasonable Utilization	*Mutatis mutandis*	Prohibition of transboundary harm	Community of interest principle	No significant harm
Delay	✓	✓		✓			✓
Redistribution		✓			✓	✓	✓
Intertwinements	✓		✓	✓	✓		
Permanence		✓	✓	✓		✓	
Scale	✓				✓	✓	✓

can result in neglecting ecological concerns. Here, the emerging legal debate with the rights-for-nature would provide a useful counterforce (e.g., Stone, 1974; Humphreys, 2017; Tanasescu, 2017; Cano Pecharroman, 2018; Chapron et al., 2019; Burgers and den Outer, 2021), ensuring that the human right to water does not exceed the meaning of the good ecological status of water. Thus, "when the rights of nature are recognized, nature is legally elevated to a subject of intrinsic value whose rights can be enforced in court" (Burgers and den Outer, 2021, p. 5). In this context, it is interesting that the no significant harm principle and the human right to water supplement each other. They do this as they jointly protect the State and the individual from significant harm done by another State to a watercourse on which they depend (see Spijkers, 2020).

In further unpacking the problem with redistribution, we note that policy strategy (b), focusing on finding sufficient evidence for policy purposes (Polasky et al., 2020), might be useful. For example, when green water (e.g., soil moisture, terrestrial evaporation, and terrestrial precipitation) is disturbed due to a heat wave – a natural hazard that is rapidly increasing in frequency due to global climate change – then the exact results that explain the dynamics around the heat wave may not be consequential. However, the existence of a severe risk of this occurring may not be enough to take action. Therefore, governance solutions should be in place at a general level that facilitate flexible re-arrangements of management in the redistribution of water functions. Here, we argue that increased support for advanced coordination efforts will be crucial, and embracing polycentric governance will enable better preparation for redistribution effects in water functions across multiple users and at multiple scales.

Hydrological *intertwinements* reflect how water-partitioning changes, water-function modifications, and other alterations in complex social-hydrological systems can result in synergies, cascades, and teleconnections (Falkenmark and Wang-Erlandsson, 2021). Unfortunately, it is difficult to model and predict where and when such effects will emerge, and we identify a couple of principles that can be used to tackle these unmeasurable effects. First, the legal principle of equitable and reasonable utilization of resources may be useful in cases when water functions are being disturbed, resulting in transboundary effects not only beyond initial logical divisions due to jurisdictions, but, for example, when teleconnections are resulting in phenomena "jumping" between regions, such as impacts on mid-latitudes precipitation caused by tropical deforestation (Liu et al., 2013). Second, since teleconnections are such an extreme phenomenon, we suggest that getting the big picture roughly right rather than focusing on details would be wise (see Polasky et al., 2020). Typically, the more teleconnections, the less understood and the more uncertain the outcomes are. Moreover, in the global hydrological cycle, progress in reducing the uncertainty of moisture recycling is impeded by limitations in validation and computation, as well as the lack of understanding of key atmospheric circulations and processes in affecting moisture transport (Gimeno et al., 2020).

In developing governance approaches for addressing intertwinements, we argue that a continuous norm development process would be beneficial as this could drive meaningful transformations and interdisciplinary learning and deliberation (Kim and Kotzé, 2020). This means that current polycentric architecture facilitates the inclusion of multiple perspectives that can enable the co-production of valuable knowledge. However, this dynamic is rarely measured but may, in turn, create both cohesion and a sense of community, and can build trust. In addition, considering the high-level intertwinements and interconnectivity between social-hydrological systems and other key Earth system processes, global water law instruments need to be viewed in light of other legislative instruments. For example, serious joint analyses of freshwater and ocean governance are key. As an example, the UN Convention on Law of the Sea needs to be addressed in water governance as interconnectivity between freshwater and sea resources occurs in areas such as river basins, mangroves, and coastal groundwater aquifers.

Additional important legislative instruments that deserve mentioning are the long-established and global-level UN Framework Convention on Climate Change (UNFCCC) (United Nations, 2021c) and the Convention on Biological Diversity (UNCBD) (United Nations, 2021d). The reason is the interconnectedness between water resources and both climate change and biodiversity loss. These sustainability problems interact with water problems in multiple ways; changes in temperature could affect river flows resulting in mobility and dilution of contaminants, or affect chemical reactions resulting in decreased water quality and hence, ecological status. Climate change also results in more frequent droughts, flash-flooding, and invasion by alien species, to mention a few examples (Whitehead et al., 2009). The UNFCCC and the UNCBD are furthermore linked from an organizational perspective as the UN hosts the secretariat for both conventions, and there exist multiple joint activities through the UNCCD, CBD and UNFCCC Joint Liaison Group (United Nations, 2001), including the establishment of a Project Preparation Facility to secure finance for large projects that can address common issues.

Hydrological *permanence* describes the situation where partitioning modifications may result in varying degrees of permanence due to system hysteresis and the cost and feasibility of restoration (Falkenmark and Wang-Erlandsson, 2021). This means that a system's transformation could result in unprecedented change, a process that may lead to new system features. In order to adapt to such a situation, we argue that the principle of *mutatis mutandis* could be used. The reason is that current legislation may be partly suitable to manage the situation. However, the need for unprecedented adaptation requires that practice presuppose the changes in the rules that are needed, even though there are no rules (yet) to manage the situation. In order to facilitate this choice, we also argue that it would be helpful to use principle (a) from Polasky et al. (2020), which suggests following the strongest and most direct path between policy decisions on outcomes. This is necessary when law and policy need to be changed significantly for achieving institutional fit. Moreover, this also requires general preparedness at the governance level, which means that we suggest using adaptive governance and the notion of complex social-ecological systems rather than ecosystems alone (see Huitema et al., 2009; Schultz et al., 2015).

The phenomenon of *scale* in social-hydrological systems refers to the problem with humans altering water functions to the extent that there is a risk of systems becoming destabilized at unprecedentedly large scales (Falkenmark and Wang-Erlandsson, 2021). The reason is that degradation and destabilization of social-hydrological systems are often the combined results of multiple interrelated perturbations of water functions. This means that not only is there a risk of destabilizing entire systems, but also a risk that this results in unintended effects in other systems, and in other jurisdictions. In these instances, the principle of prohibition of transboundary harm needs to be used. However, jurisdictional divisions can be problematic in some cases of water function destabilization, as many watersheds and reservoirs themselves are transboundary. This is something that current global water law, to some extent, has already taken into account. However, in the Water Convention, transboundary effects are considered in terms of water resources, not water functions. At the same time, addressing the phenomenon of scale in global instruments would be extremely difficult, and we suggest using principle (d) by Polasky et al. (2020) to aim for getting the big picture roughly right. Hence, the details of water functions may be unmeasurable, and the general hydrological science may be much more helpful to take note of when designing solutions that can tackle problems of scale. However, the transboundary effects are still a crucial hurdle in this case. We therefore suggest broadening sources of authority, scopes of legitimacy, and effectiveness to go beyond the State (see Kotzé, 2019).

This framing for guiding the application of Earth system law to social-hydrological problems is only a first step in using Earth system law concepts to identify future reforms for global water law and governance. As evident from Table 3, the legal principles we analyze still fall short, as there are gaps in how they jointly can grapple with the complexity of the global hydrological cycle in the Anthropocene. We may even need additional principles, in addition to reforming existing regulatory architecture. At the same time, we wish to point out that including details of water functions in considerations of future regulatory solutions for social-hydrological systems does not mean we are suggesting that there is a need for a new distinct field of law (see Kotzé, 2020). However, the need for increased attention to water functions is to be considered – if aiming to improve institutional fit for social-hydrological systems – while still operating within a legal system largely premised on the same basic principles.

5. Conclusions and future research directions

The global hydrological cycle is characterized by complex interdependencies and self-regulating feedbacks that keep water in an ever-evolving state of flux at local, regional, and global levels. Increasingly, the scale of human impacts in the Anthropocene is altering the dynamics of this cycle, and legal regimes for governing water are not presently able to address these challenges effectively. Drawing on research of complex social-hydrological systems, we illustrate the pressing need to integrate scientific understanding of the global hydrological cycle from the physical sciences with insights from the broad environmental governance and legal scholarship. We argue that there is not only a need to address "institutional fit" between global hydrological processes and legal and regulatory systems, but that this disconnect – and the consequences thereof – is deeply rooted in the Anthropocene. New modes of thinking are therefore required to develop solutions for governing water as a cycle and integrated social-hydrological system.

In this article, we use Earth system law to illustrate an approach for addressing the features of core hydrological problems in the Anthropocene – delay, redistribution, intertwinements, permanence, and scale – and which recognizes the evolving interconnections between the global hydrological cycle and human society. While global problems, these problems nevertheless have impacts at the local and regional levels, where existing governance institutions predominantly operate. Importantly, Earth system law has the flexibility to incorporate various legal principles, place-based knowledge and practices, and other successful elements of previous institutional reforms. To this end, we propose a simple framework for applying Earth system law to core hydrological problems (Table 3) using a principle- and rights-based approach to water governance. This approach enhances the role of legal principles further and integrates particular policy principles, which together can be an entry point for improving water governance in the Anthropocene. These improvements are the result of strengthening institutional fit between the structure of the governance system and the specific characteristics of the problems at hand.

Earth system law can play a key role in guiding research on the global hydrological cycle and the many diverse water governance regimes found around the world, and advancing new ways of thinking about social-hydrological systems and governance solutions in the Anthropocene. While important knowledge gaps remain, this is an ongoing and active field of research (e.g., Blöschl et al., 2019; Gleeson et al., 2020; Wouters et al., 2020). This research is fundamentally driven by the recognition that the uncertainty underlying global hydrological dynamics in the Anthropocene will continue to challenge regulatory regimes. This uncertainty is something that Earth system law, through connecting with existing legal principles and instruments, can begin to address. While our focus in this article has been on the global hydrological cycle, the same basic approach can also be used to disentangle other complex global social-ecological processes, such as the carbon, nitrogen, and phosphorous cycles. There are no panaceas in the domains of law and governance, however, the Earth system law paradigm provides a valuable framing for future research on many of society's most pressing sustainability challenges.

CRediT authorship contribution statement

Hanna Ahlström: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Jacob Hileman:** Conceptualization, Methodology, Resources, Validation, Writing – review & editing. **Lan Wang-Erlandsson:** Conceptualization, Methodology, Resources, Writing – review & editing. **María Mancilla García:** Conceptualization, Writing – review & editing. **Michele-Lee Moore:** Writing – review & editing. **Krisztina Jonas:** Writing – review & editing. **Agnes Pranindita:** Visualization, Writing – review & editing. **Jan J. Kuiper:** Writing – review & editing. **Ingo Fetzer:** Writing – review & editing. **Fernando Jaramillo:** Writing – review & editing. **Uno Svedin:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the editors Louis Kotzé, Rakhyun E. Kim, Catherine Blanchard and the anonymous reviewers for their helpful comments and feedback. We would like to thank the Task Force on Earth System Law and the Earth System Governance network; the ideas for this paper have been developed during workshops and task force meetings over the course of several years. We also want to thank Rosa Manzo for her helpful input and comments. We benefitted from presenting an earlier version of this paper at the 2021 Bratislava Earth System Governance conference. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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