Illuminating water cycle modifications and Earth System resilience in the Anthropocene

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Abstract (<250 words max; currently 215)

Fresh water – the bloodstream of the biosphere – is at the centre of the planetary drama of the Anthropocene. Water fluxes and stores regulate the Earth's climate and are essential for thriving aquatic and terrestrial ecosystems, as well as water, food and energy security. But the water cycle is also being modified by humans at an unprecedented scale and rate. A holistic understanding of freshwater's role for Earth System resilience and the detection and monitoring of anthropogenic water cycle modifications across scales is urgent, yet existing methods and frameworks are not well suited for this. In this paper we highlight four core Earth System functions of water (hydroclimatic regulation, hydroecological regulation, storage, and transport) and key related processes. Building on systems and resilience theory, we review the evidence of regional-scale regime shifts and disruptions of the Earth System functions of water. We then propose a framework for detecting, monitoring, and establishing safe limits to water cycle modifications, and identify four possible spatially explicit methods for their quantification. In sum, this paper presents an ambitious scientific and policy Grand Challenge that could substantially improve our understanding of the role of water in the Earth System and cross-scale management of water cycle modifications that would be a complementary approach to existing water management tools.

Plain language summary (<200 words max; currently 185)

Freshwater is crucially important for all life on Earth. There is abundant research and evidence on how different processes within the water cycle regulate climate and support ecosystems – and by extension, human societies. Humans are also a major force disturbing those processes and modifying the water cycle. These modifications include, for instance, surface water withdrawals, groundwater pumping, deforestation and other land cover change, and ice melt due to warming climate. As most previous research on human-water interactions focuses on understanding systems at smaller scales, such as a watershed or a nation, comprehensive understanding of what human modifications of the water cycle mean for the stability of the planet is still lacking. In this paper we propose a new framework for analyzing and establishing limits to a variety of human modifications of the water cycle, to ensure that the stability of the Earth would not be compromised. We see this as an important and urgent scientific challenge that has the potential to substantially improve our understanding of the functioning of the Earth System and to inform local and global policy towards a more sustainable future.

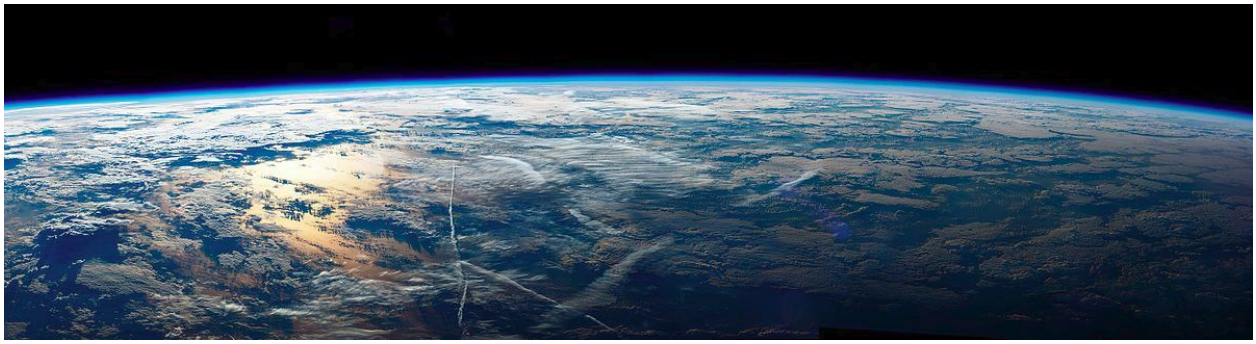
Three key points:

- Earth System resilience depends on an improved understanding and management of water cycle modifications
- We identify four key functions of freshwater in the Earth System and evidence of regional to global regime shifts and disruptions
- The water planetary boundary is a compelling framework to improve our understanding and management of water cycle modifications in the Earth System

Brief summary

The water cycle is the bloodstream of Earth, yet it is startling that we do not know if human modifications of the water cycle will cause major disruptions of the Earth System. By reviewing water's role in the Earth System, and regions where the water cycle is already being disrupted, we present an ambitious scientific and policy Grand Challenge to improve our understanding of the role of freshwater in the Earth System and water management.

Featured image



Caption: Sunrise panorama taken from the International Space Station - the perfect place to ponder planetary scale modifications to the water cycle.
Credit and Source: NASA, https://commons.wikimedia.org/wiki/File:Sun_Glint_over_Atlantic_Ocean.jpg

Societal relevance:

Water, food and energy security depend on a water cycle which we are modifying in a number of ways.

Social media:

- **Twitter handles:** @water_undergrnd, @ZipperSam, @sthlmresilience, @lan_wang, @PIK_Climate, @PIK_Klima, @jrockstrom, @JayFamiglietti, @KateBrauman, @LineGordon,@SarahLizCornell, @usask_water, @UViCIVE; @IIASAVienna; @BristolUniWater, @WaterBier, @tarajtroy
- **Factoid:** Water has four key functions in the Earth System

1. Why is a framework for examining the role of water cycle modifications for Earth System resilience necessary?

Human pressure on fundamental planetary processes has pushed the Earth out of the geological epoch Holocene, the only period in Earth's history known to be capable of supporting sedentary, complex human civilisation. In this newly human shaped Anthropocene, the scale and magnitude of

human drivers risk triggering critical transitions that jeopardize the habitability of Earth for human society (Barnosky et al., 2012; Steffen et al., 2018). Fresh water - the bloodstream of the biosphere - is at the center of this planetary drama: the water cycle is not only essential for myriad Earth System processes, interactions, and feedbacks, but it is also subject to anthropogenic manipulation at the global scale. Water, food and energy security and sustainability depend on various water stores and fluxes that have been and are being modified by many and diverse processes, interactions and feedbacks of global change in the Anthropocene.

Water flows regulate the Earth's climate system through mediation of the energy, carbon, and water balances, and are a prerequisite for thriving aquatic and terrestrial ecosystems. Among others, soil moisture affects the Earth's albedo through supporting vegetation and contributing to cloud formation, carbon sequestration through regulation of biomass production, and moisture feedback on precipitation. Rivers transport half of the carbon sequestered by land to water bodies and respire half into the atmosphere (Biddanda, 2017). Critical ecosystem services require 90% of global evapotranspiration to function (Rockström et al. 1999), while streamflow sustains aquatic ecosystem functioning (Smakhtin 2004).

Holistically understanding, evaluating, and maintaining the water cycle's role for a resilient Earth System is extremely challenging and urgent in the Anthropocene, as the societal complexities interlock with the complex dynamics of the Earth System. Globally distributed and interconnected human activities have become the dominant force of modifications to the water cycle, and already created local-to-regional scale water-mediated regime shifts. Research shows anthropogenic forcing to dominate changing river flows worldwide (Shiklomanov and Rodda 2003), groundwater depletion (Aeschbach-Hertig & Gleeson, 2012; Bierkens & Wada, 2019), the partitioning of water on land (Jaramillo and Destouni, 2015a) as well as the spatial patterns and seasonal timing of evapotranspiration over continents (Gordon et al. 2005; Sterling et al., 2012). These water cycle modifications have had knock-on effects on critical Earth System functioning through modification of atmospheric moisture feedbacks (Wang-Erlandsson et al., 2018), tropical forest resilience (Hirota et al., 2011; Zemp et al., 2017; Staal et al., 2019), monsoon systems (Boers et al., 2017), and sea-level (Wada et al., 2012). At the same time, the human impact on the water cycle is more internationally connected than ever, through flows of people, commodities, finance, technology, and information that enable emerging impacts on the water cycle through virtual water flows (Dalin et al., 2017; Oki et al., 2017; Porkka et al., 2012; Hoekstra & Mekonnen, 2012), land grabs (Rulli et al., 2013), and forest transition displacements (Meyfroidt et al., 2010).

The spatial heterogeneity and distribution of the water cycle, however, mean that water stores and fluxes are often analysed at local to regional scales of 10s to 1000s of km^2 (Archfield et al., 2015; Brown et al., 2015; Medema et al., 2008; Savenije et al., 2014). A textbook case of the need for a continental-to-global, rather than local-to-regional, perspective is the global interconnectedness between the Amazon Forest and the water cycle. Greenhouse gas emissions worldwide drive climate change that increases the frequency and severity of drought and fire in the Amazon (Aragão et al., 2018; Duffy et al., 2015), while global demand for agricultural products such as soybean and financial investments spur forest clearing (Barona et al., 2010; Galaz et al., 2018; Nepstad et al., 1994). Together, deforestation and climate change alter the regional rainfall patterns and shift the South American monsoon system, and reverberate to impact on precipitation in the midlatitudes through teleconnections (D'Almeida et al., 2007; Lawrence and Vandecar, 2014; Nobre, 2014; Spera et al. 2016,

Swann et al., 2015). Moreover, repeated severe droughts may ultimately undermine the Amazon forest's role as a global net carbon sink (Yang et al., 2018).

The scientific and ethical grand challenge of examining water cycle modifications for Earth System resilience is deeply connected to numerous research questions at the heart of current research frontiers and questions in hydrology: How do we understand and manage the interactions, dynamics, and connectivities in the global water system? (Alcamo et al., 2008; Bierkens, 2015; Bierkens et al., 2015; Fan et al., 2019; Vörösmarty et al., 2015; Wood et al., 2011). How do we consider humans as endogenous to the water system in the relatively newly emerging discipline of socio-hydrology? (Baldassarre et al., 2013.; Brown et al., 2015; Lund, 2015; Montanari et al., 2013; Sivapalan et al., 2012, 2014; Vogel et al., 2015; Wagener et al., 2010). How do we manage tradeoffs between global development considered in the Sustainable Development Goals (Bhaduri et al., 2016) and increasing pressure on the Earth System functioning of the global water cycle? How do existing water management and governance mechanisms and institutions respond to and influence global water cycling? How do interactions and feedbacks with the food and energy sectors impact the water cycle across scales? (Cai et al., 2018). Examining global water cycle modifications is a logical complement to these research challenges. To be able to navigate the planetary-scale dynamics of the water cycle and make connections to these other research questions, we first need to understand:

- What water-related changes may lead to supra-regional or global tipping points - or more gradual yet equally detrimental transitions - related to water and Earth System functions?
- To what water-related changes, and in what regions, is the Earth System particularly vulnerable?
- How do local changes in stores and fluxes of water impact regional and global processes, and how do regional and global changes impact local processes?

In addition to these scientific questions, ideally a framework should also be developed that recognizes all members of the global community as stakeholders of the global water cycle as a 'global commons' and provides knowledge of globally distributed and aggregated limits to various water cycle modifications beyond which we may push the Earth System state into uncharted territory in terms of habitability for human civilisations.

Our objective is twofold: providing a planetary-scale overview of water's role for maintaining Earth System functions, and developing a framework for monitoring, detecting, and potentially acting on water cycle modifications. This work is based on multiple workshops, working groups and intense collaboration and debate. Throughout we focus on Earth System resilience using a series of concepts introduced in Section 2 (dynamic systems, resilience theory, Earth System science and the planetary boundary framework). Many manuscripts and textbooks have described the components and interactions of the stores and fluxes of the water cycle but few (Falkenmark et al., 2019; Rockström et al., 2014) have highlighted the global water cycle as a dynamic, resilient system as we do in Section 2. We then synthesize the functional role of water in the broader Earth System (Section 3) and the evidence of regional regime shifts and disruptions of the Earth System functions of water (Section 4). Finally, we propose a framework for defining global water cycle modifications using the planetary boundary framework (Section 5) and conclude with a call to join us in this Grand Challenge (Section 6). In the future, the methods for monitoring and detecting water cycle modifications could possibly be modified or adapted to examine other issues such as water scarcity, security or virtual water. Herein 'water' refers to terrestrial freshwater.

2. Earth System resilience theory

To motivate the following overview of resilience theory, we start with the potential role of human modifications of the water cycle in planetary-scale Earth System regime shift. Regime shifts are abrupt, persistent, and possibly irreversible changes in the system's structure and function, that in general are well-documented across scales (Biggs et al., 2018; Rocha et al., 2015). Well-known local-to-regional scale regime shifts in hydrological systems include lake eutrophication even occurring in large lakes such as Lake Victoria (Hecky et al., 2010), lake depletion such as Lake Aral (Micklin, 2007; Micklin et al., 2016), and salinization such as in the Murray-Darling river basin (Overton et al., 2006). However, regime shifts occur also at the planetary scale. Known Earth System regime shifts include the last glacial-interglacial transition (Hoek, 2008), the 'Big Five' mass extinctions (Barnosky et al., 2011), and the Cambrian explosion (Marshall, 2006). The evidence and understanding of past regime shifts in the Earth System is important, as current human pressure already exceeds the rate and magnitude of the forcings that precipitated the latest global-scale regime state shift, the last glacial-interglacial transition (Barnosky et al., 2012).

In general, regime shifts of a social-ecological system can occur through either a controlling parameter (such as rainfall) crossing a critical threshold leading to a 'tipping' into a new state with internally stabilizing feedback processes, or collapse through gradual change (Falkenmark et al., 2018). Regime shift through critical thresholds result in a state change that may be difficult or impossible to reverse due to the triggering of reinforcing positive feedbacks, whereas a regime shift through linear collapse of internal features or sub-systems refers to a gradual system change that does not necessarily introduce significant differences in system feedbacks. Regime shift through threshold effects and reinforcing feedbacks can be illustrated through deforestation in the Amazon: loss in moisture supply leads to rainfall reduction, which leads to forest loss below certain rainfall threshold, thus further rainfall reduction associated with increased risk of fire and further forest loss (Zemp et al., 2017). To restore the rainforest is more difficult because it involves hysteresis behavior enforced by internal feedbacks: in the Amazon example, counteracting self-amplifying feedbacks to restore a forested state requires higher rainfall levels than the threshold that originally induced forest loss. On the other hand, an example of linear collapse can be illustrated through river depletion, where water levels in principle water levels can be restored by reversing the processes that led to their depletion (although related social-ecological systems such as fishing communities may exhibit hysteresis effects). To our best knowledge, there is no study comprehensively investigating whether human modifications of the water cycle have led, could be leading, or will lead to planetary-scale regime shifts in the Earth System.

The term *resilience* was originally introduced to refer to *the capacity of a system to absorb or withstand disturbance* that may precipitate a regime shift. This definition of resilience is sometimes referred to as *persistence resilience*; it draws originally from system dynamics understanding and is supported by a range of observation-based ecosystem studies (e.g., Holling 1973; Scheffer et al., 2001; Walker et al., 2004). Persistence resilience can be used to describe all the examples of regime shifts described above and deals primarily with an agent-free environment (Donges and Barfuss, 2017), and therefore is also of primary relevance for understanding the biophysical aspects of Earth System resilience. Broader aspects of *resilience* of social-ecological systems (e.g., Holling 1973, Folke et al. 2004,

Holling and Gunderson, 2002) include the capacity of a system to *adapt* tochange and *transform* into a new desirable state. Complex interlinked social-ecological systems may undergo cycles of adaptation at different hierarchical levels which are nested in the panarchy framework (Holling and Gundersson, 2002). At the global scale and highest level, social-ecological system dynamics have been addressed using world-system analysis (Wallerstein 1974, Denemark et al. 2000, Chase-Dunn and Hall 1997, Hall 2000; Gotts, 2007) that to varying extent address socio-economic feedbacks equally with biophysical feedbacks. The branch of Earth System science focusing on Earth System resilience to anthropogenic pressure that does not consider socio-economic feedbacks as endogenous, includes studies of tipping elements in the Earth System (Lenton et al., 2008; Steffen et al., 2018) and the planetary boundary framework (Rockström et al., 2009; Steffen et al., 2015).

Specifically, this paper focuses on the water cycle's essential role for Earth System resilience, that is the Earth System's ability to absorb or withstand perturbations and other stressors while essentially maintaining its structure and functions (see Sect. 3). We recognize the three ways in which water interacts with resilience (Rockström et al., 2014, Falkenmark et al., 2019): as ''source" of resilience, i.e., through the generation of ecosystem services and functions in both terrestrial and aquatic systems, as ''victim" of change, e.g., by being subject to land-use change and pollution pressure, and as ''agent" of change, e.g., by driving social shocks or vegetation change through modifications in the temporal or spatial distribution in the water cycle. By undermining resilience of local-regional systems, human modifications of the water cycle have already pushed many of them beyond collapse, such as through salinization, desertification, flow regulation and eutrophication (see Sect. 4 for evidence of water-related regime shifts).

In the Anthropocene, continued human pressure may now accumulate water cycle modifications to threats of planetary-scale tipping through four general pathways (Barnosky et al., 2012; Lenton et al., 2008; Steffen et al., 2018, Rocha et al., 2018): (1) extensive local scale changes that trigger critical transitions over a large area; (2) global forcing that trigger local changes; (3) synergy, feedbacks, and cross-scale interactions through complex networks; and (4) tipping of major subsystems of the Earth System**.** The categorisation of these pathways is idealised, and multiple mechanisms may concur in reality. The first pathway is supported by empirical patch-area and landscape-scale studies. For example, crossing certain thresholds of habitat loss or fragmentation may trigger abrupt, landscape-wide species extinction (Pardini et al., 2010). At Earth System scale, it has been suggested that a 50% transformation of the Earth's terrestrial ecosystems may cause global scale tipping to occur (Noss et al., 2012) and e.g., that 85 % of tropical and boreal forests need to remain in order to safeguard the functioning of the Earth System (Rockström et al., 2009; Steffen et al., 2015). The second pathway can be illustrated by the role of Amazon as carbon sink, which if reverted to carbon source through drought-induced forest loss, may cause a global scale forcing that triggers local-scale changes in the water cycle. The third pathway is supported by network analyses that show that regime shifts may interact through cascades and cross-scale interactions (e.g. Rocha et al., 2018). Dynamic and complex interactions and cascades have also raised the concern that processes that were previously thought to be confined to regional concern, may in fact have planetary resilience implications (Rocha et al., 2019, Lenton et al., 2008, Steffen et al., 2018). Finally, the fourth pathway suggests that human pressure on tipping elements, that is the key subsystems of the Earth at subcontinental scale that can be switched into a different state following

minor perturbations (Lenton et al., 2008), may have the ability to destabilize the current planetary state (Steffen et al., 2018).

We seek to understand the role of water cycle modifications for Earth System dynamics through the lens of the planetary boundary framework (Sect. 5), as it is to date the most systematic effort for comprehensively addressing the question "What are the non-negotiable planetary preconditions that humanity needs to respect in order to avoid the risk of deleterious or even catastrophic environmental change at continental to global scales?" (Rockström et al. 2009). Planetary boundaries are defined as biogeophysical boundaries for the processes and systems which together regulate the state of the Earth System; the framework is not to be confused with the 'planetary boundary layer' used in in atmospheric science (Vilà-Guerau de Arellan et al., 2015). The planetary boundary framework is based on (i) identifying relevant biogeochemical processes that regulate the stability of the Earth System and (ii) determining the limit of human perturbation of these critical processes. Crossing any of the planetary boundaries could destabilize essential Earth System processes (Rockström et al., 2009a, 2009b; Steffen et al., 2015b) and move the Earth away from Holocene conditions during which human societies developed and proliferated. Nine planetary boundary processes and systems have been identified (Rockström et al., 2009). For each boundary process/system, the planetary boundary should be defined based on the relationship between a control variable (a quantifiable, possibly spatially distributed biophysical indicator of main processes controlling the Earth System process in question, over which humans can exert some influence) and a response variable (an aspect of the Earth System that defines Earth's stable Holocene-like conditions and is affected by a change in the control variable), though several planetary boundaries do not yet have clearly defined control and/or response variables. It is important to note that the planetary boundary framework is based on biophysical resilience (the ability of a system to absorb or withstand disturbance, and possibly ecosystems' ability to adapt to changing conditions) rather than the more socio-ecological resilience that includes societal adaptation, transformation and panarchy.

The current planetary boundary for human freshwater use is based on a global sum of the average annual surface water consumptive use from rivers, reservoirs, lakes, and aquifers. Even if refined by complementary subglobal boundaries representing rivers' environmental flow requirements (Gerten et al., 2013, Steffen et al., 2015), this provisional planetary boundary and its current status have been critiqued (Heistermann, 2017; Jaramillo & Destouni, 2015b; Gleeson et al., submitted) as it does not reflect all types of human interference with the complex global water cycle and Earth System. Gleeson et al. (submitted) suggests that a water planetary boundary would be more scientifically robust and more useful in decision-making frameworks if it was redesigned to consider more specifically how climate and living ecosystems respond to changes in the different forms of water on Earth: atmospheric water, soil moisture, groundwater and frozen water, as well as surface water. In Section 5 we suggest how the planetary boundary framework can be used to better understand how water cycle modifications could potentially be impacting Earth System resilience, based on our following review.

3. The Earth System functions of water

The water cycle or hydrosphere is a complex system with different stores interacting with varying strengths and over a wide range of scales with other components of the Earth System such as

atmosphere, biosphere and lithosphere (Figure 1). Building on previous attempts in the systems and resilience literature (Rockström et al., 2014) and seminal hydrology evaluations, reports and textbooks (Dingman, 2002; National Research Council, 1991; Oki & Kanae, 2006; Tang & Oki, 2016; UNESCO, 1978) here we highlight four core *Earth System functions of water*: (1) hydroclimatic regulation, (2) hydroecological regulation, (3) storage, and (4) transport. These Earth System functions of water are different from *watershed functions* (Black, 1997; Wagener et al., 2007) which focus on hydrologic functions generally at smaller scales, not explicitly considering water in the broader Earth System. The Earth System functions of water are also different to *water functions for social-ecological resilience* in the Anthropocene (Falkenmark et al., 2019) that distinguish green and blue water functions for social-ecological resilience, whereas we focus on the functions of water explicitly for Earth System stability, independent of green or blue origin. Inevitably, this description and related citations are non-exhaustive, and serve primarily to outline a scientific foundation examining global water cycle modifications and for the water planetary boundary.

Hydroclimatic regulation: Water exchange between the atmosphere, land surface, soil, ice and snow masses, and groundwater regulates the Earth's climate system through mediation of the energy, carbon, and water balance. Water vapour is the most powerful greenhouse gas due to its infrared absorption spectrum, heat storage capacity, and abundance in the atmosphere (Mitchell, 1989; Rodhe, 1990). Additionally, water vapour also forms clouds that reflect incoming solar radiation and absorb outgoing longwave radiation, with an overall effect on the Earth's energy balance that depends on cloud thickness, altitude, and constituent particles. Water vapor and the evaporation-condensation cycle is also the primary mechanism by which heat is redistributed from the equator to the poles (Henshaw et al., 2000). Soil moisture, surface water, and frozen water all directly or indirectly influence the albedo of the Earth's surface, and thus the radiative balance. Soil moisture availability and surface water further affect carbon sinks and sources through mediating photosynthesis, oxygenation of soil, carbon transport, and carbon storage (IPCC, 2013). About half of the carbon sequestered by land is transported by rivers to water bodies, of which half is respired into the atmosphere (Biddanda, 2017). Finally, precipitation is influenced by evapotranspiration from land and soil moisture through boundary layer dynamics (Guillod et al., 2015), moisture recycling (van der Ent et al., 2010), and atmospheric circulation regulation (Tuinenburg, 2013). It should be noted that this core function has been undergoing major changes during the Anthropocene because of global climate change which is often referred to as the "intensification" of the water cycle as reviewed by (Huntington, 2006), and a recent framework has been proposed for quantifying this intensification (Huntington et al., 2018).

Hydroecological regulation: Water's hydroecological function enables and connects life on land and in aquatic ecosystems, and creates and sustains the ecosystems that human societies and Earth System stability depend on (Gerten, 2013). This hydroecological function can be described by the quantity of water present at different times within the year relative to an ecosystem's water requirements. In aquatic ecosystems, this role of freshwater is often referred to as 'environmental flows' (Acreman et al., 2014; Poff et al., 2009; Poff & Matthews, 2013). In terrestrial systems, the quantity and timing of available water relative to a species' physiological requirements is assigned as 'hydrologic niche' and, along with other environmental constraints, drives species composition and ecosystem function (Booth & Loheide, 2012; Deane et al., 2017; Henszey et al., 2004). Changes to the quantity and timing of water availability can impact biosphere integrity and make ecosystems more vulnerable to

drought or flooding, and/or enable the invasion of non-native species (Catford et al., 2014; Pool et al., 2010; Zipper et al., 2017). Water's hydroecological functions are closely connected to its hydroclimatic and storage functions. Almost all water stored on land is of atmospheric origin, and surface waters (streams, lakes, and wetlands) harbor various types of aquatic ecosystems. Moreover, groundwater stores buffer aquatic ecosystems from the effects of short-term climatic variability. Hydroecological regulation is also closely tied to water's transport function as sediment and nutrient fluxes are critical determinants of aquatic habitat formation (Belmont & Foufoula-Georgiou, 2017; Motew et al., 2017; National Marine Fisheries Service, 2016).

Storage: Freshwater storage in groundwater, lakes, wetlands, reservoirs, and frozen water primarily interacts with the Earth System as a control over sea level and albedo. Globally, freshwater storage is dominated by frozen water in the polar ice sheets (Gleick, 2000). Mass loss due to ice melt is widespread and accelerating in both the Antarctic and Greenland ice sheets (Velicogna et al., 2014), and melt from the ice sheets increases the total volume of water in the oceans leading to sea level rise, exacerbated by thermal expansion of the oceans caused by global warming (Abraham et al., 2013). Groundwater is the second largest store of freshwater and reductions in global groundwater storage due to groundwater pumping are a secondary contributor to global sea level (Wada et al., 2016), though the magnitude of this flux is dwarfed by the impacts of ice melting (Reager et al., 2016). Storage also plays a critical role in buffering the response of hydrological systems to short-term hydroclimatic variability. Increased storage in surface reservoirs plays only a minor role in total global water volume storage, yet it has the capacity to substantially distort river flow regimes, including the drying up of streams, and to reduce hydrologic connectivity (Grill et al., 2019). Loss of storage due to changes in lakes and wetlands, groundwater depletion or reduced snowpack and/or mountain glaciers may also impact the Earth System via locally-important alterations to the timing, magnitude and temperature of streamflow (Dickerson-Lange & Mitchell, 2014; Gleeson & Richter, 2018; Immerzeel et al., 2010; Watson et al., 2014), which can have cascading effects on ecosystems and society (Xu et al., 2009).

Transport: The spatial and temporal dynamics of water are fundamental for moving, displacing and diluting sediment and dissolved constituents including nutrients on the surface or within soils (Earle et al., 2015). Chemical weathering, mineral soil leaching and transport of artificial fertilisers and chemicals into adjacent rivers, lakes and streams, and finally into the oceans (Earle et al., 2015; McGuire & McDonnell, 2006) impacts water quality and biodiversity (Smith & Schindler, 2009). Water can either stabilize or destabilize landscapes (e.g. flooding) (Earle et al., 2015; Summerfield, 2005, 2014). Deposition of soil by water flux within and between these shape and determine the function and geological shape of landscapes (Ellis et al., 2002; Wiens et al., 2005). Water and ice are responsible for a large amount of sediment transport on the surface of the Earth and are important in many geological processes such as rock and landform formation and erosion (Earle et al., 2015; Summerfield, 2005, 2014). Dilution of minerals and nutrients in soil additionally controls soil- and aboveground biome characteristic (Ellis et al., 2002; Tölgyessy, 1993; Wiens et al., 2005).

4. Evidence of regional regime shifts and disruptions of the Earth System functions of water

Evidence of global water cycle modifications on Earth System functions is scattered, so here we highlight the existence and also the limitations of current knowledge of regional regime shifts and possible tipping elements for each water store. We point out key knowledge gaps that are essential to examine in the process of assessing water cycle modifications. The water stores are discussed in counter-clockwise order in Figure 1a starting with atmospheric water, while acknowledging that water stores are intimately and inherently interlinked, so considering them separately can be challenging. Evidence of local to regional regime shifts is ample, and can potentially lead to non-linear disruptions of the Earth System functions of water related to hydroclimatic and hydroecological regulation and storage through cross-scale interactions and cascading effects (Rocha et al., 2018; Steffen et al., 2018).

Atmospheric water: The atmospheric water store fuels precipitation and is replenished by evapotranspiration and ocean evaporation. Here, we focus on the direct linkages between precipitation modification and hydroecological regime shifts, as well as evaporative change and regime shifts in hydroclimatic systems.

The Amazon rainforest is identified as a tipping element in the Earth System (Lenton et al., 2008, Steffen et al 2018) with multiple alternative stable states primarily governed by precipitation (Hirota et al., 2011). A critical transition from evergreen rainforest to seasonal forest or savanna can have major consequences beyond the regional scale due to carbon release (Houghton et al., 2000), induced tipping of the South American monsoon system (Boers et al., 2017), precipitation reduction (Zemp et al., 2017), and biodiversity loss (Malhi et al., 2008). Climate change and deforestation critically undermine the resilience of the Amazon forest. The position of the climate change-induced threshold is uncertain due to a large spread in models' ability to simulate precipitation, fire feedback, and ecosystem response, among others (Cox et al., 2013; Huntingford et al., 2013; Nobre & Borma, 2009). The threshold of deforestation-induced Amazon forest dieback has been suggested to be between 10% and 40% depending on definitions and extent of forest transition considered (Nobre & Borma, 2009; Pires & Costa, 2013). The Congo rainforest and Southeast Asian rainforests are other less investigated tropical forest regions exhibiting similar regime shift mechanisms and consequences for Earth System functions as the Amazon forest (Bell et al., 2015; Lawrence & Vandecar, 2015; Staver et al., 2011). In temperate regions, drought conditions and considerable reductions in precipitation have been proven to trigger rapid coniferous forest declines in the southwestern United States. The tipping point has been found to be the persistence of an intense water deficit over 11 months (Huang et al., 2015). Small changes in precipitation regimes are also known to have induced structural changes in wetland ecosystems and abrupt ecological transitions in coastal wetlands are expected to expand to new coastal wetlands as hydroclimatic changes step up in the future (Osland et al., 2016).

Monsoons are large scale seasonal reversals of atmospheric circulation mediated by the asymmetric heating of land and ocean. The rainy phase of monsoon brings large amounts of precipitation, turning landscapes from deserts to grasslands and are crucially important for agriculture and ecosystems. Because monsoons are mediated by a land-ocean temperature gradient, studies have

also shown that evapotranspiration (i.e., latent heat) over land areas can affect the monsoon. For example, Tuinenburg (2013) showed that the onset of the Indian summer monsoon is delayed by evapotranspiration from irrigation. Nogherotto et al. (2013) showed that decreased evapotranspiration over deforested areas in the Congo has a seasonal influence on the strength of the West and south-equatorial African monsoon. (Zeng, 2003) suggest that an increased albedo by overgrazing reinforces the duration and severity of dry spells in the Sahel through a prolonged weakening of the West African Monsoon. Boers et al. (2017) showed that deforestation can induce a tipping point in the South American monsoon. Shifts in monsoon systems can have abrupt consequences at the continental scale. For example, the West African monsoon shift had a major influence on the stable states between the Green Sahara state (11,000-5,000 years ago) and the current Desert Sahara state (Tierney et al., 2017; Yu et al., 2015).

Soil moisture: Soil moisture mediates terrestrial ecosystem transitions and desertification processes. Decrease in soil moisture caused by vegetation loss, topsoil erosion, and compaction, creates a self-reinforcing feedback that prevents the re-establishment of plants (e.g., Whitford et al., 2006; Karssenberg et al., 2017)(Karssenberg et al., 2017) or causes shifts in ecosystem species composition (Loheide & Gorelick, 2007). Soil moisture-related land degradation has the potential for cascading and teleconnected impacts on the Earth's energy balance through e.g., large-scale albedo change, and desert dust that follows wind beyond continents with effects on both climate systems and nutrient balance in distant regions (Bestelmeyer et al., 2015; Geist & Lambin, 2004). Also, deficits in soil moisture and changes in terrestrial water storage can severely diminish the primary production and CO_2 sequestration capacity of the terrestrial biosphere (Humphrey et al., 2018). Important soil carbon storage and sequestration regions are the Northern Hemisphere that has the largest soil organic carbon stocks, and the tropics that have seen the largest decrease in carbon stocks due to agricultural expansion (Cherlet et al., 2018).

Surface water: While aquatic ecosystems can be negatively impacted by changes in streamflow (Carlisle et al., 2017; Gido et al., 2010; Perkin et al., 2017; Vörösmarty et al., 2010), there is no clear evidence or mechanism by which local- or basin-scale changes in aquatic biosphere integrity could scale up to have a planetary impact. However, one local-scale tipping point related to aquatic ecosystems is the transition of streams from perennial to intermittent, which can lead to a reorganization of local food webs (Bogan & Lytle, 2011). This transition is likely to be driven by changes in the groundwater storage function of water, which acts as a buffer against short-term hydroclimatic variability by providing a stable supply of baseflow to streams. A second local-scale hydroecological tipping point that has been identified in the literature is food web collapse associated with eutrophication and salinization. For the perennial-ephemeral and oligotrophic-eutrophic regime shifts, evidence of tipping points to eutrophic states (Wang & Temmerman, 2013) or even lake disappearance by water use-induced drying exist in several regions around the world, the most well-known being the Aral Sea (Shibuo et al., 2007). We are not aware of studies that look beyond an individual body of water to trigger widespread shifts in Earth System function. Finally, various species- to ecosystem-level effects, in particular for migratory species, have been documented in river ecosystems due to reductions in hydrologic connectivity (Pringle, 2003) caused by the global proliferation of anthropogenic dam and barrier construction (Grill et al., 2019).

Wetland ecosystems are rich in water-dependent biodiversity and play a multifaceted role for many Earth System processes, including high rates of evapotranspiration and groundwater recharge, temporary water storage, and sediment exchange. Large wetland complexes located downstream of streams and rivers may experience stress-induced tipping points due to variations in their hydrological characteristics. Also, coastal wetlands with mangrove ecosystems under such stress can experience reductions in their mangrove development and extensive mangrove mortality (Jimenez et al., 1985; Smith, 1992; Twilley & Rivera-Monroy, 2005); reductions of freshwater inputs to coastal wetlands or hydrological modification of their natural flows and connectivity due to reservoirs have already resulted in massive mangrove mortality episodes involving hypersalinity conditions in several wetlands around the world from which the wetlands have not been able to completely recover (Barreto, 2008; Cintron et al., 1978; Jaramillo et al., 2018; Jimenez et al., 1985).

Finally, surface water flows can affect Earth System processes due to their natural freshwater, sediment and nutrient delivery to coastal zones and the ocean. Reductions in these flows, due to either climate or anthropogenic impacts including sediment trapping in reservoirs, may shift the balance between aggradation and erosion rates of large river deltas leading to land loss and cascading effects in marine ecosystems (Syvitski et al., 2009; Tessler et al., 2018), including their ability to sequester carbon (Duarte et al., 2004). Altered flows can potentially affect global ocean circulation systems through changes in salinity and temperature; for example, changes in Arctic runoff may affect Arctic ocean stratification, circulation and ice cover (Nummelin et al., 2016) with implications for global oceanic circulation, including the Atlantic overturning meridional circulation and thermohaline circulation.

Groundwater. Several potential groundwater-related tipping points are associated with the storage function of groundwater. Most critical for aquatic ecosystems is the role of groundwater as a stable supply of baseflow, and therefore a key tipping point is when a stream transitions from perennial to intermittent (Bogan & Lytle, 2011) due to groundwater depletion (see 'Surface Water' subsection above). However, groundwater-related tipping points are also present for terrestrial groundwater-dependent ecosystems. Groundwater within or near the root zone provides a stable supply of water, particularly during drought, for many natural and agricultural crops via capillary rise and direct groundwater uptake (Booth et al., 2016; Brown et al., 2011; Eamus et al., 2015; Rohde et al., 2017; Zipper et al., 2015, 2017). Numerous examples exist for critical transitions associated with regional-scale impacts of changes in groundwater storage, including groundwater depletion leading to riparian forest loss (Scott et al., 1999), rising groundwater levels leading to widespread flooding in Argentina (Houspanossian et al., 2016; Kuppel et al., 2015), and loss of dry forests leading to regional salinization in Australia (Clarke et al., 2002; George et al., 1999) and the Chaco region of Argentina (Giménez et al., 2016; Marchesini et al., 2017). Since groundwater is estimated to influence terrestrial ecosystems over 7-17% of global land area (Fan et al., 2013) and can contribute substantially to evapotranspiration (Lowry & Loheide, 2010; Soylu et al., 2011, 2014; Yeh & Famiglietti, 2009), it likely constitutes an important component of terrestrial evapotranspiration. Thus, important groundwater-dependent ecosystems which may contribute to regional-scale shifts could potentially have a proportionally larger influence on Earth System dynamics. For instance, groundwater is an essential contributor to evapotranspiration in the Amazon basin (Fan et al., 2017; Miguez-Macho & Fan, 2012).

Frozen water: Unlike the other water sub-boundaries, global tipping elements associated with frozen water storage have been studied extensively due to their potential contributions to global sea level rise. While mass loss due to the melting of grounded glacial ice is widespread and accelerating in both the Antarctic and Greenland ice sheets (Velicogna et al., 2014), the West Antarctic Ice Sheet is the primary keystone region associated with the frozen water boundary and is thought to be vulnerable to tipping-point type dynamics, which would occur if ocean water was able to undercut the ice sheet and rapidly accelerate melt (Feldmann & Levermann, 2015; Lenton et al., 2008; Notz, 2009; Rignot et al., 2004). The collapse of the West Antarctic Ice Sheet would lead to an estimated 5m of sea level rise, which is comparable in magnitude to the total sea level change over the past ~7000 years (Fleming et al., 1998). While the loss of Arctic sea ice would have impacts on regional and global climate due to reduced albedo, and is a distinctive marker of alternate states of the Earth System, its melting sea ice would not impact sea levels (Bathiany et al., 2016; Notz, 2009; Tietsche et al., 2011). Widespread destabilization of permafrost is another potential tipping point related to frozen water (Lenton et al., 2008), as permafrost thaw leads to the release of greenhouses gases which are a positive feedback on climate change and cause increasing sediment transport (Bring et al., 2016; Syvitski, 2002). There is increasing evidence for abrupt thaw mechanisms at local scales (Chasmer & Hopkinson, 2017; Chipman & Hu, 2017; Schuur et al., 2015; Zipper et al., 2018), though at global scales permafrost thaw is thought to be a gradual source of carbon of approximately the same magnitude as land use change over the next century (Schuur et al., 2015).

5. Understanding Earth System resilience impacts of global water cycle modifications using the planetary boundary framework

5.1 Why use the planetary boundary framework?

Section 4 provides clues and hints of key regions and processes that could be important for identifying global water cycle modifications but does not deliver a systematic process for monitoring and detecting these. As discussed in section 2, the planetary boundary framework is, to our best knowledge, the only systematic effort for defining and monitoring the key processes and systems, which together regulate the state of the Earth System, the global water cycle being one of them. Monitoring human modifications of the global water cycle might be possible even without a systematic framework, but we argue that using a formalised framework, such as the planetary boundaries, is a pragmatic approach that will lead to scientific insight and implementation in governance and management - while accounting for the intrinsic embedding of the water cycle in the Earth System. More significant scientific insights are possible because the planetary boundary framework rests on the foundations of decades of resilience research (described in Section 2) and has been much discussed in multiple scientific communities. Additionally, this formalized framework links to other important current research areas in hydrology and other disciplines (described in Section 1) which may lead to synergistic developments in multiple research strands. Stronger implementation in governance and management is also more likely as demonstrated by planetary boundaries already being considered in some governance and corporate management contexts (Clift et al., 2017; Galaz et al., 2012; Häyhä et al., 2016, 2018).

An additional benefit for governance and management is that the planetary boundary framework provides a useful bridge to water governance and management by formalizing the concept of the 'safe operating space' for humanity. The safe operating space concept provides a set of quantitative scientific targets to keep the Earth within the relatively stable climatic conditions of the Holocene during which modern society developed By setting the boundaries at a 'safe' distance from scientifically defined dangerous levels or thresholds, the framework also involves normative judgements about how we choose to deal with risk and uncertainty. Various other water management indicators measure impact and status of water resources but do not explicitly connect these resources to Earth's habitable conditions, such as water stress (Alcamo et al., 2007; Falkenmark, 1989; Smakhtin et al., 2004; Vorosmarty et al 2000), water depletion (Brauman et al., 2016), water scarcity (Brauman et al., 2016; Kummu et al., 2016), water footprints (Hoekstra & Mekonnen, 2012), groundwater footprints (Gleeson et al., 2012), water wedges (Wada et al., 2014), water use regimes (Weiskel et al., 2007), human appropriation of evapotranspiration (Gordon et al., 2005), and hydroclimatic separation (Destouni et al., 2012). The planetary boundaries framework complements this with information about the proximity of unwanted state shifts in Earth System stability, thus adding a simple aspirational metric to the toolbox.

Following Gleeson et al. (submitted) we argue that although a planetary boundary for water is useful as a concept, the current definition and methodology does not adequately represent the role of water in the Earth System and should therefore be revised to reflect the key Earth System functions of water described in Section 3. In the following subsections we propose a framework for a more robust analysis of global water cycle modifications using the planetary boundary framework, but similar approaches could be used to monitor and detect global water cycle modifications outside the framework.

5.2 Planetary sub-boundaries for water stores

In order to adequately represent the complexity and heterogeneity of the water cycle, we use the five stores (Section 3) of water to divide the water cycle into planetary sub-boundaries that represent different processes and functions of water as proposed by Gleeson et al (submitted). Based on the five water stores, six planetary sub-boundaries (Figure 3) together represent the most important processes and crucial functions of water in the Earth System. Each store has a single sub-boundary based in a preliminary analysis of the core function of this store except atmospheric water that has two possible planetary sub-boundaries since atmospheric water has two distinct and important functions (hydroclimatic and hydroecologic):

The Earth System function and process addressed by each of the proposed sub-boundaries are shown in Figure 3 and summarized below (with each **process** in **bold**):

● one atmospheric water sub-boundary focuses on the importance of **evapotranspiration** for climate pattern stability or land-atmosphere coupling stability (hydroclimatic regulation);

● second atmospheric water sub-boundary focuses on the role of **precipitation** in maintaining biomes, which is connected to biodiversity (hydroecologic regulation);

● soil moisture sub-boundary focuses on **carbon uptake** or **net primary productivity** (hydroclimatic regulation);

● surface water sub-boundary focuses on **streamflow** and related habitat that maintains aquatic biodiversity (hydroecologic regulation);

● groundwater sub-boundary focuses on **baseflow** or **sea level rise** that are important to aquatic biodiversity (hydroecologic regulation) or the oceans (storage), respectively;

● frozen water component focuses on **ice sheet** volume which is important to sea level rise in the oceans (storage).

Possible control variables and suggested response variables are compiled in Figure 2. It is important to note that the proposed water planetary sub-boundaries do not represent the transport function of water, as these aspects are already considered in a separate 'biogeochemical flows' planetary boundary. Outside the planetary boundaries framework, additional indicator(s) representing the transport function might need to be added.

5.3. Methodological questions of scale and data

To monitor and detect global water cycle modifications, a number of methodological issues must be addressed. First are questions of space and time scales to consider in the analysis. Figure 2c summarizes the spatial aggregation appropriate for each of the suggested planetary sub-boundaries and respective control variables. For example, the surface water and groundwater components could be analyzed at the large basin and regional aquifer scale, respectively. Time scales to consider depend on how the desirable baseline conditions against which current or future conditions may be compared are defined. The planetary boundary framework considers the Holocene epoch, yet robust global hydrologic data and models generally start in the ~1950s due to availability of widespread instrumental records and key datasets (Bierkens, 2015; Wada, 2016). This is also broadly consistent with the timing of the 'great acceleration' that is sometimes considered the onset of the post-Holocene Anthropocene (Steffen et al., 2015a; Zalasiewicz et al., 2015). We suggest ~1950s (or before if possible) as a Holocene-like 'baseline' condition, understanding that this does not include all anthropogenic disturbances.

Second, a useful approach for monitoring and detecting global water cycle modifications will be model-agnostic but does require some uniformity in the quantification approach. We argue that the appropriate approach requires explicit accounting of climate feedbacks, impacts on aquatic and terrestrial biodiversity, and other coupled impacts between the water cycle and Earth System stability in order to test relationships between control and response variables. Most existing global hydrologic models have only limited ability to simulate these feedbacks (Bierkens, 2015; Sood & Smakhtin, 2015). For example, global hydrological simulations used to quantify the current water planetary boundary (Steffen et al., 2015b) were not dynamically coupled to a general circulation model. It is likely that adequately assessing global water cycle modifications in the way we propose will necessitate revised models that robustly represent all water stores and their interactions with other parts of the Earth System or else better coupling with other models.

Input data in two different spatial perspectives may be useful for different water stores (see Weiskel et al 2014 for longer discussion and definition): hydrologic units (distributed, open-systems represented as pixels or raster cells) or semi-closed units (such as watersheds, aquifers, etc.). For example, for the surface water store, a semi-closed approach using large basins or river networks might

be appropriate whereas, for the hydroclimatic function of the atmospheric water store (Figure 3), a distributed hydrologic system may be best since atmospheric water flows across traditional hydrological boundaries such as watershed divides (e.g., Bosilovich et al. 2002, Dirmeyer et al., 2009, van der Ent et al. 2011, Wang-Erlandsson et al., 2018)(Chen et al., 2019). Also, for each water store, either hydrologic fluxes or the rate of change of hydrologic fluxes may be be useful. The rate of change of hydrologic fluxes could be driven by a myriad of global change processes such as water use, land use, or climate change. An argument for the rate of change rather than the hydrologic fluxes is that the rate and time scale of environmental change may be more important to Earth System adaptation than absolute thresholds. Using streamflow as an example, aquatic ecosystems thrive in regions with a wide range of streamflow rates, but rapid change in streamflow could be problematic.

5.4. Spatial analysis of critical regions of global water cycle modifications using the planetary boundary framework

To provide more methodology to water cycle modifications and water in the planetary boundary framework, we propose four new methods of spatial analysis (Figure 3). The current methodology for the freshwater use planetary boundary (or any other methodology that involves summing water fluxes) masks both the spatial and temporal heterogeneity of the water cycle and implies that resilience loss caused by water impacts in one place can be remediated by water abundance in another place. Each of these methods quantify the impact of water cycle modifications on Earth System resilience using control and response variables on the horizontal and vertical axis, respectively, and thus may also in the future be useful for setting water planetary sub-boundaries. Possible control and response variables for each water store are shown in Figure 2. The first three methods use input data described in Section 5.3 whereas the last method uses previously mapped tipping elements (Lenton et al 2008). The first three methods use four different types of data depending on the store: data in hydrologic units or semi-closed units as well as data as fluxes or rate of change of fluxes (Section 5.3).

1) The ‘unweighted approach’ calculates the percentage of global land that has crossed a certain threshold using either the hydrologic fluxes or the hydrologic rate of change and the spatial perspective described in Section 5.3. For example, for the surface water sub-boundary, the control variable could be the percentage of global land area of basins (or percentage length of river network to not bias by river length) not meeting environmental flow requirements; the input data would be at the scale of semi-closed units of basins or river networks (e.g. De Graaf et al. (2019)). This approach would be useful if widespread degradation of conditions or change of fluxes or stores leads to significant change in the response variable. Another example is for the hydroclimatic function of atmospheric water store (Figure 3a), where the percentage area that exceed a certain level of evapotranspiration change could be considered.

2) The ‘weighted approach’ calculates the percentage of the global land area that has crossed a certain threshold *weighted by the importance of that hydrologic unit to the Earth System function* (also at a defined scale of analysis). This ‘weight’ is multiplied with the data used in the ‘unweighted approach’. For example, again for the surface water sub-boundary, the control variable could be the percentage of global land area of basins not meeting environmental flow requirements *weighted by aquatic biodiversity*. This approach implies there are regions where the Earth System function of water

for the sub-boundary makes a more important contribution to the response variable. Another example is for the hydroclimatic function of atmospheric water store (Figure 3b), where evapotranspiration change that influences precipitation more through moisture recycling can be given a higher weight than evapotranspiration changes that have less influence on precipitation.

3) The 'keystone region approach' identifies regions where certain water stores are disproportionately important to specific Earth System components. The concept of keystone regions is inspired by the concept of 'keystone species', a species that produces a major impact on their ecosystem and are considered essential to maintaining optimum ecosystem function or structure (Mills et al., 1993), as well as the Pareto Principle, also known as the 80-20 Rule (Pareto, 1896). We hypothesize that a small number of regions (the '20' in the Pareto Principle) have a disproportionate impact on the stability of the Earth System. We define a keystone region as a region where a water store produces a disproportionately important impact and could be essential to maintaining an Earth System component (e.g. atmospheric water in the Amazon is disproportionately important to the global climate system)**.** 'Disportionately important' refers to the risk of direct or cascading impacts on other systems or regions following local or regional destabilization. For example, the Pareto Principle could be used to identify the 20% of land area with the greatest weighting (e.g., aquatic biodiversity in the previous example) and exclude all other regions from global aggregation. For example for the hydroclimatic function of atmospheric water store (Figure 3c), where the areas with the highest moisture recycling ratio are considered keystone regions.

4) 'Tipping elements' uses previously identified tipping elements in the Earth System (Lenton et al 2008). Tipping elements are defined as subsystems of the Earth System that are at least subcontinental in scale and can be switched - under certain circumstances - into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point - in forcing and a feature of the system - at which the future state of the system is qualitatively altered (Lenton et al., 2008) in a regime shift. For example, for the hydroclimatic function of atmospheric water store (Figure 3d), the monsoon systems could potentially be considered as atmospheric water tipping elements

Different methods may be more effective or appropriate for each water store and water planetary sub-boundaries. A mixture of the most effective and appropriate methods for each water planetary sub-boundary could be used in setting the final planetary boundaries since the existing framework is based on a variety of different methods and metrics (Rockström et al., 2009a). Although the weighted approach, keystone region approach, and tipping element approach might all identify regions of hydrologic importance in global change, there are important differences between them. Tipping elements focus on cohesive sub-systems and identifying regime shifts whereas the keystone region approach focuses on cumulative and additive impacts across the Earth system which may not be a cohesive sub-system and do not necessarily exhibit tipping behavior. The weighted approach also focuses on cumulative impacts but is less likely to result in cohesive regions than the keystone region method. All four approaches are different than other approaches to identify regions of hydrologic importance in global change, like previous discussions of 'water towers' since the approaches here focus on changes to the Earth System whereas 'water towers' focus on the importance of specific regions for water resources.

5.5. Acting upon water cycle modifications by setting and using water planetary sub-boundaries

The process of setting 'fully elaborated' planetary sub-boundaries with clearly defined relationships between control and response variables for the different water stores may take a considerable amount of time (at least ~5-10 years, comparable to other global change science synthesis activities). Yet there is significant interest in using the water planetary boundary, so we explored setting interim planetary sub-boundaries based on global standards for carbon and existing global data (see Appendix for additional justification and description of the interim boundary). Interim planetary boundaries for water could be set by quantifying the change in proposed control variables for each water component under the Representative Concentration Pathways (RCP) with related emissions and land use scenarios consistent with the UNFCCC Paris Agreement. In other words, these are the water boundaries that would arise if global carbon governance actors considered water impacts. These new boundaries could support water governance that increasingly addresses global issues through global water initiatives across sectors (Varady et al., 2009). Theoretical exploration of global water governance highlights a combination of multilevel design with a strong global dimension (Hoekstra, 2006; Pahl-Wostl et al., 2008). Global water governance could also be an integral part of a proposed Earth System governance framework (Biermann et al., 2012), integrated into existing global carbon governance, or ideally developed as another parallel form of global governance.

We suggest that the water planetary boundary provides an effective framework that can integrate with and complement existing water management approaches at sub-global scales such as watersheds, aquifers, or nations. Sub-global use of the water planetary boundary is the focus of separate work (Zipper et al., submitted) and we only briefly introduce it here to highlight the potential utility of the water planetary boundary. Previous work with the planetary boundary framework at sub-global scales has either attempted to calculate a 'fair share' of the planetary boundary value allocated to a sub-global domain, e.g. a nation (Häyhä et al., 2018); or use the control-response variable relationship foundational to the planetary boundary framework to develop local boundaries in a conceptually consistent manner (e.g., Dearing et al., 2014). Most critically, the planetary boundary framework allows water managers to account for potential global Earth System impacts of local water cycle modifications (e.g., local responsibility for global environmental challenges), a perspective not captured in existing water management frameworks. Given the lack of global water management and governance organizations, effective integration of water management across local- to global-scales may require innovative governance structures and approaches (Biermann, 2012; Galaz et al., 2012).

6. Concluding with an invitation to meet a Grand Challenge

The core functions of hydroclimatic regulation, hydroecological regulation, storage and transport illuminate how water stores (atmospheric water, soil moisture, surface water, groundwater, and frozen water) are inextricably interconnected with Earth System components such as the

atmosphere, land, and ocean through processes, mechanisms, and variables that are familiar to all hydrologists such as evapotranspiration, albedo, ice melt, streamflow etc. The scientific and ethical grand challenge of examining water cycle modifications for Earth System resilience are motivated by the numerous research questions we introduced in Section 1. The grand challenge first focuses on which water-related changes may lead to supraregional or global tipping points or gradual adverse transitions in critical water and Earth System functions (Section 2 and 3). A related question inherently relates to scaling between regional and global processes for which we provide new methods of analysis (Section 5.4). Setting new water planetary sub-boundaries (Section 5.5) may enable managing tradeoffs between global development (e.g. the Sustainable Development Goals) and increasing pressure on global water resources, which may motivate the development of water governance mechanisms and institutions that respond to and influence global water cycling. Finally, interactions and feedbacks from other systems such as food and energy drive many of these processes, so focusing on water cycle modifications may provide insights or tools for other initiatives.

We invite the hydrology and water resource community to apply serious and sustained attention toward understanding water cycle modifications and Earth System resilience, which could be transformative to our understanding of socio-hydrologic systems across scales, up to the global, and provide a new approach for global hydrology modeling and analysis. We suggest three initiatives that can be tackled immediately and simultaneously by highly collaborative working groups from diverse backgrounds:

- Initiative 1 could compare the 'weighted approach' to the 'keystone region approach,' which could uncover differences in regions that are disproportionately important to different Earth System functions of water.
- Initiative 2, focusing on the rate of change of fluxes, could uncover the regions of the world experiencing the most rapid rates of change and investigate whether these have meaningful impact on different Earth System functions of water.
- Initiative 3 could identify and provisionally quantify interim, spatially explicit planetary sub-boundaries (which may not be possible or robust for all the planetary sub-boundaries).

Together, these three initiatives would lay the foundation for developing fully elaborated water planetary sub-boundaries and illuminating water cycle modifications in the Anthropocene. This ambitious scientific agenda also directly leads to important water policy implications. We therefore end with an invitation to the hydrology and water resources community to join us in following this Grand Challenge, which would initiate numerous interesting scientific journeys and help set precautionary planetary boundaries for water that reflect its undeniable importance in global sustainability and Earth System science.

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Figures

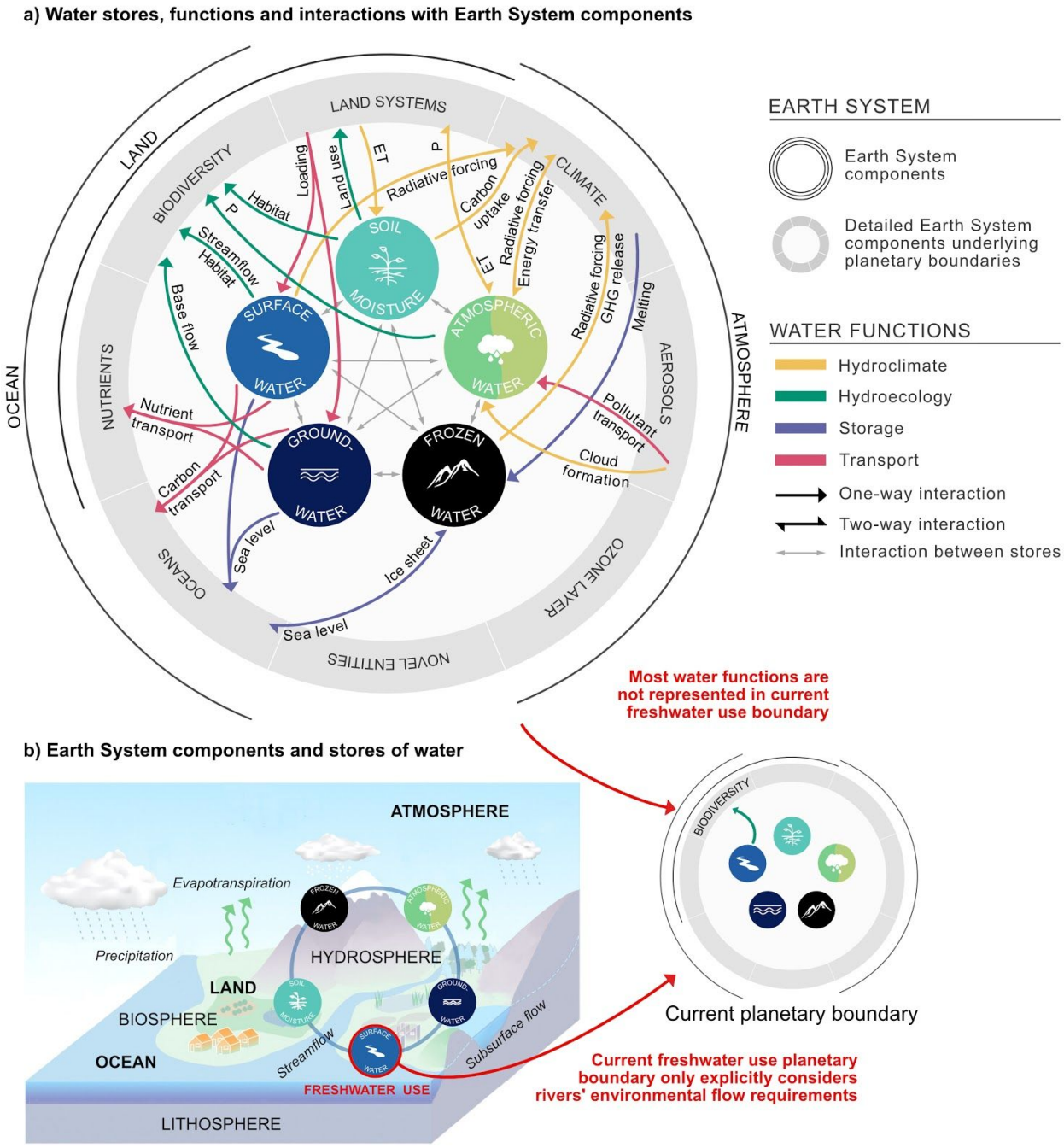
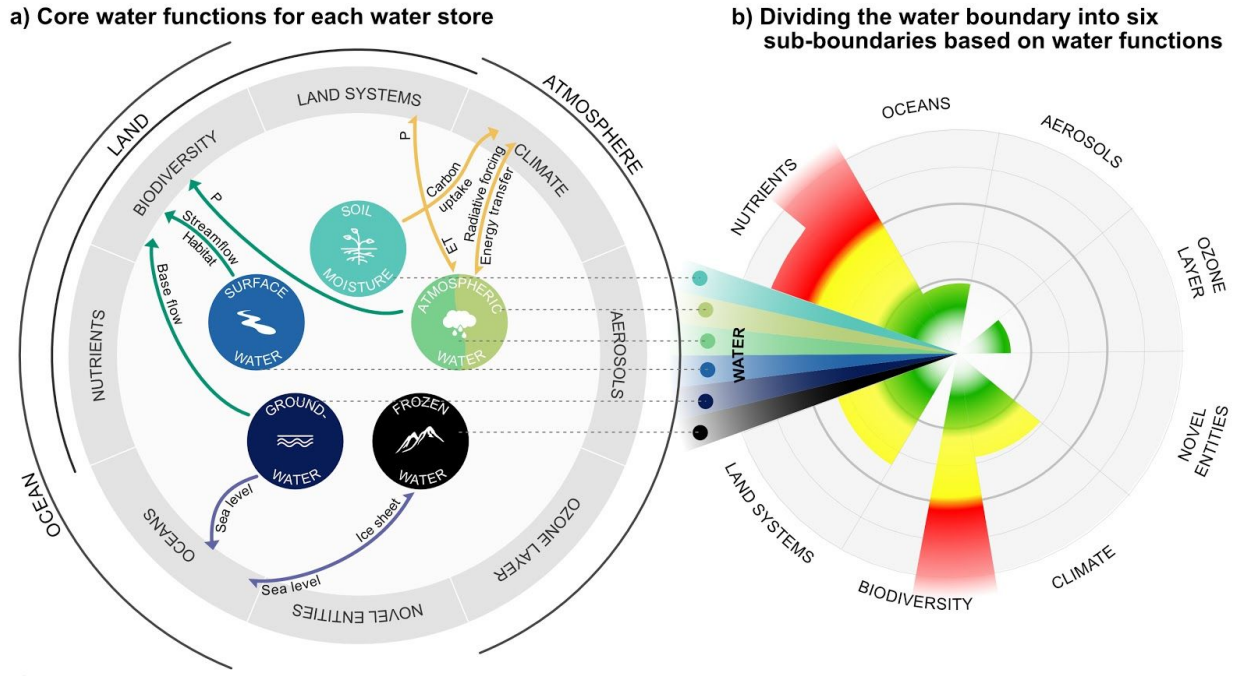


Figure 1. (a) The core functions of water in the Earth System. The five stores of the freshwater hydrosphere (colored circles in center), major components of the Earth System (outer ring), and detailed Earth System components underlying the different planetary boundaries (inner grey ring) are shown. The arrows denote processes linking the water stores and the Earth System components, color-coded by water function (hydroclimate, hydroecology, storage, and transport). Since we focus on the near-surface hydrosphere, we consider land (part of the lithosphere) and ocean (part of the hydrosphere) as important related Earth System components. The interaction between stores are shown schematically but are not the focus since these are described in many hydrology textbooks. This diagram highlights the complex interactions between water stores

and Earth System components more comprehensively than b) common representations of the water cycle (modified from Oki and Kanae, 2006). Freshwater use is one of the current planetary boundaries, yet affecting only a small component of (b) the hydrosphere and only representing a single function of water in the Earth System (see inset small circle and red text). Note that in figures, hydroclimatic and hydroecological regulation are shorted to hydroclimate and hydroecology; P is precipitation and ET is evapotranspiration.



c) Key aspects of each of the proposed water sub-boundaries

	ATMOSPHERIC WATER (hydroclimate)	ATMOSPHERIC WATER (hydroecology)	SOIL MOISTURE (hydroclimate)	SURFACE WATER (hydroecology)	GROUNDWATER (storage)	FROZEN WATER (storage)
Possible scale of analysis	Distributed hydrologic unit	Biomes or hydroclimatic regimes	Biomes or land cover groups	Large basins or river networks	Regional aquifers	Global
Possible response variable(s)	Climate pattern stability or land-atmosphere coupling stability	Terrestrial biosphere integrity (species richness or species/area)	Carbon uptake or net primary production	Aquatic biosphere integrity (species richness or species/area)	Terrestrial or aquatic biosphere integrity, or sea level rise	Sea level rise
Possible interim planetary boundary	Percentage of global land area with evapotranspiration change within range of simulated future	Percentage of global land area with precipitation change within range of simulated future	Maintenance of global net primary productivity at or above levels under simulated future	Percentage of basins or total river length within environmental flow limits under simulated future	Percentage of basins with low flows meeting or exceeding simulated future	Volume of ice melt to keep sea level within limits under simulated future

Figure 2. a) Each water store has core water function(s) to maintain Earth System resilience (see Section 3). , which could help quantify impacts of global water cycle modifications using the planetary boundary framework, also lead to (b) Defining water planetary sub-boundaries based on the functional relationship between water stores and Earth System components (c) Suggestions for key aspects of each of the six sub-boundaries including possible interim planetary boundary based on 2°C target for late this century. The key water function for each sub-boundary is identified in parentheses (such as hydroecology for surface water).

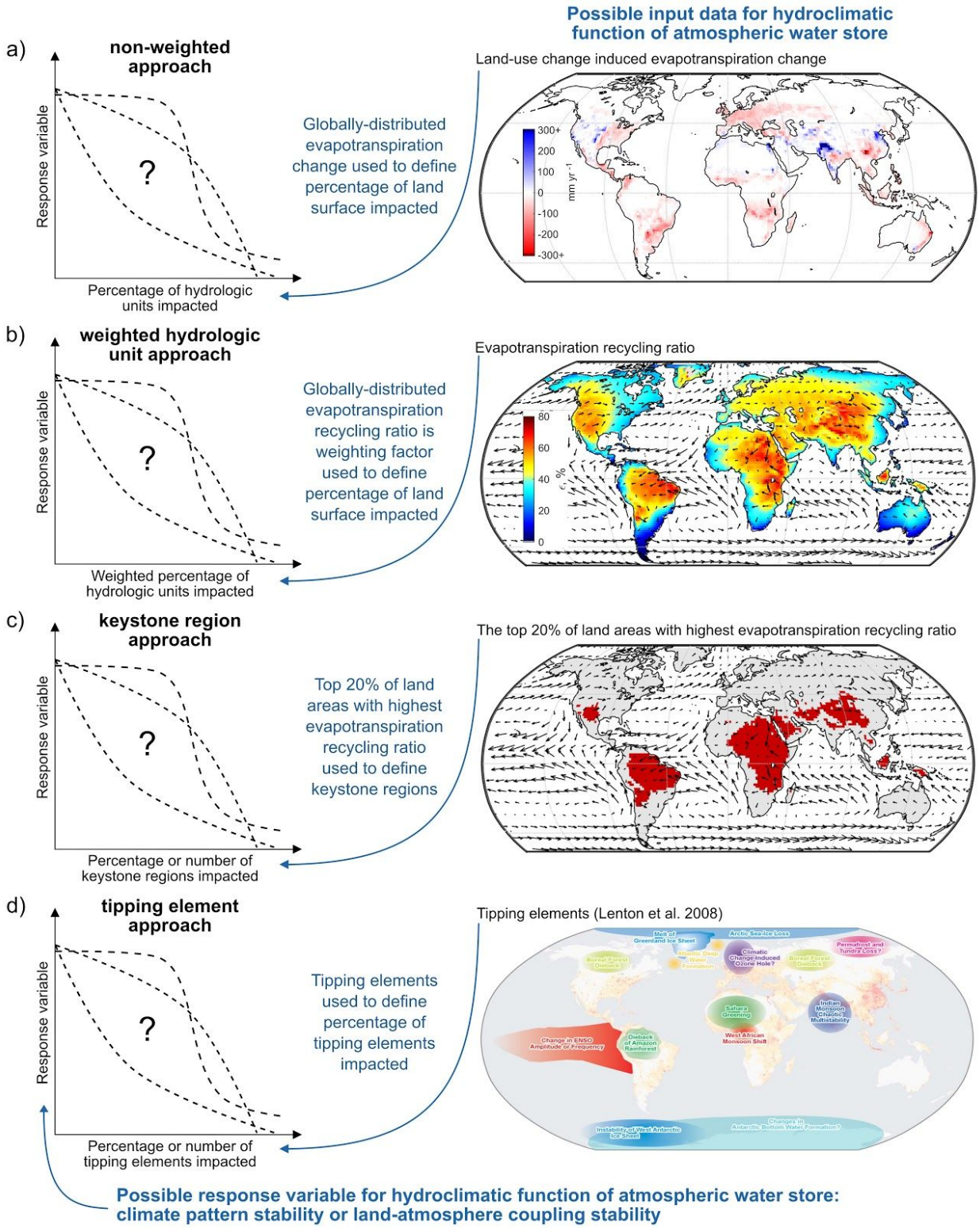


FIgure 3. Methods for the spatial analysis of critical regions of global water cycle modifications using the planetary boundary framework (control and response variables of graph). Example of using the hydroclimatic function of the atmospheric water store for illustrative purposes.