The water planetary boundary: a roadmap to illuminate water cycle modifications in the Anthropocene

Submitted to *Water Resources Research* for consideration for *"Grand Challenges Special Edition"*

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Key points:

- The water planetary boundary is a compelling concept that could motivate and improve our understanding and management of water cycle in the Earth System

- The current planetary boundary for freshwater use should be replaced since it does not adequately represent the role of water in influencing critical Earth System functions
- We identify key functions of water in the Earth System and propose an ambitious roadmap for identifying new water planetary sub-boundaries

Abstract

The planetary boundaries framework has proven useful for many global sustainability contexts, but is challenging to apply to freshwater, which is spatially heterogeneous, part of complex socio-ecological systems and often dominated by local dynamics. To date, the planetary boundary for water has been simplistically defined by as the global rate of blue water consumption, functioning as a proxy for water partitioning in the global hydrological cycle, and considering impacts on rivers' environmental flow requirements. We suggest the current planetary boundary should be replaced since it does not adequately represent the influence of water in critical Earth System functions such as regional climate and biodiversity. We review the core functions of water in the Earth System and set out a roadmap towards a more robust, holistic, and locally applicable water planetary boundary. We propose defining the boundary using four core functions of water (hydroclimatic regulation, hydroecological regulation, storage, and transport) in conjunction with five water stores (surface water, atmospheric water, soil moisture, groundwater and frozen water). Through the functions, the stores are inextricably interconnected with the atmosphere, land, ocean and biosphere. The roadmap presented here outlines how to clarify tipping points, keystone regions, cross-scale propagation of impacts, and the functional relationships of water stores in the Earth System. We also identify four spatially explicit methods for sub-boundaries quantification: hydrologic units, weighted hydrologic units, rate of change, and keystone regions. In sum, this is an ambitious scientific and policy Grand Challenge that could substantially improve our understanding and management of water cycle modifications in the Earth System and provide a complementary approach to existing water management tools.

Plain language summary (<200 words)

The planetary boundaries framework proposes quantified guardrails to human perturbation of global environmental processes that regulate the stability of the planet, safeguarding a Holocene-like status of the Earth System, and has been widely adopted in sustainability science, governance, and corporate management. However, the planetary boundary for human freshwater use has been applied much less. It is based on a global sum of the average annual surface water use from rivers, reservoirs, lakes, and aquifers. This measure does not reflect all types of human interference with the complex global water cycle and Earth System. We suggest that the water planetary boundary will be more scientifically robust and more useful in decision-making frameworks if it is 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 addition, we outline four different approaches for the future quantification of the sub-boundaries. This paper provides an ambitious scientific roadmap to define a new water planetary boundary consisting of sub-boundaries that account for a variety of changes to the water cycle.

1. The challenges and possibilities of a water planetary boundary

1.1 The current planetary boundary for freshwater use

The current ‘freshwater use’ planetary boundary, one of nine planetary boundaries, is based on allowable human blue water consumptive use (Figure 1). The planetary boundaries, a global environmental sustainability framework for identifying critical transitions or tipping points in the complex, interacting Earth, based on control and response variables (see Box 1 for an overview of the planetary boundary concept and Table 1 for definitions). The control variable for the current freshwater use planetary boundary has been set at 4,000 km^3/year blue water consumption, the lower limit of a 4,000 - 6,000 km^3/year range that is considered a danger zone as ‘it takes us too close to the risk of blue and green water induced thresholds that could have deleterious or even catastrophic impacts on the earth system’ (Rockström et al., 2009b). Rockström et al. (2009b) suggested blue water consumptive use as a proxy variable because it functionally integrates the three largest anthropogenic manipulations of the water cycle: human impacts on precipitation patterns, modifications of soil moisture by land use and land cover; and water withdrawals from discharge for human use; it was not intended to be an explicit variable implying that water use can or should be aggregated to global scales. Focusing on water withdrawals, Gerten et al. (2013) proposed quantifying the boundary by assessing the amount of streamflow needed to maintain environmental flow requirements in all river basins on Earth, which suggests a freshwater use planetary boundary in the range of 1,100-4,500 km^3/year.

While the planetary boundary framework garnered interest from international bodies such as the United Nations (Leach et al., 2013) as well as from the corporate sustainability sector (Clift et al., 2017a), the water planetary boundary has seen limited uptake in water resource management, policy, and governance. A number of jurisdictions have estimated their local contributions to the water planetary boundaries (Campbell et al., 2017; Cole et al., 2014a; Häyhä et al., 2016a, 2018a), though it is not clear that these exercises have led to concrete policy outcomes. In turn, the water planetary boundary is often not included in global assessments of water and the environment. This lack of uptake is likely due to the conceptual and methodological over-simplifications of the current freshwater use planetary boundary (see Appendix for summary of previous critiques), which raises the fundamental question of the relevance or value of a water planetary boundary for environmental governance, and for water management, specifically.

INSERT FIGURE 1 HERE

1.2 The relevance of a water planetary boundary for water management and environmental governance, and our understanding of socio-hydrologic systems across scale

Water has been identified as one of the planetary boundaries highlighting the critical role water has in the functioning and stability of the Earth system and that water is fundamentally inextricable from other parts of the Earth System and other planetary boundaries. The ‘raison d’être’ for the concept of a water planetary boundary lies in the need for humanity to consider and govern the multiple, critical roles water has in the functioning and stability of the Earth System, and the habitability of Earth for humankind (Rockström et al., 2014). Defining a water planetary boundary could and should be part of the large and growing field of water resource management, which addresses the constantly evolving nexus of hydrology, society, and economics (Konar et al., 2016; Montanari et al., 2013; Sivapalan et al., 2012, 2014; Wagener et al., 2010). Adding a simplified aspirational metric to the toolbox does not suggest that spatial heterogeneity of water issues should be ignored or local-scale data or metrics should be superseded. The water planetary boundary is useful because it serves a distinct and complementary purpose to other water resources management methods, tools and frameworks in four ways:

- Considering water flows beyond traditional basin boundaries. Research on virtual water flows (Oki et al., 2017; Porkka et al., 2012), moisture transfer (Keys et al., 2012; Wang-Erlandsson et al., 2018) and regional groundwater flow (Gleeson & Manning, 2008; Tóth, 1963) together suggest that basin-scale approaches could be complemented by, and nested within approaches and metrics at scales beyond basins and even to global scales (Vörösmarty et al., 2015).
- Acknowledging that all water cycle flows and stocks are important to humanity and the Earth System, rather than just blue water flows and stocks, which are often the focus of water resource management for water supply, flood control and aquatic habitat management (Falkenmark & Rockstrom, 2006). Expanding the focus on water cycle dynamics, the interactions between water cycle and other Earth System components, and the dependence of the terrestrial biosphere (including human societies) on green water more holistically and realistically represent the complex interactions between humanity and the water cycle.
- Providing an assessment of the 'safe operating space' for humanity (Box 1). Various water management indicators measure impact and status such as water stress (Alcamo et al., 2007; Falkenmark, 1989; Smakhtin et al., 2004), water depletion (Brauman et al., 2016), water scarcity (Brauman et al., 2016; Kummu et al., 2016), water footprints (Hoekstra & Mekonnen, 2012), water wedges (Wada et al., 2014), water use regimes (Weiskel et al., 2007), human appropriation of evapotranspiration (Gordon et al., 2005; Postel et al., 1996), and hydroclimatic separation (Destouni et al., 2012). These could be complemented by information about the proximity of unwanted state shifts.
- Recognizing that all members of the global community are stakeholders in local-to-regional scale functioning of the water cycle. Eventually, disaggregating the water planetary boundary to a specific basin or jurisdiction could yield results and concerns for managers, policy makers or stakeholders that are different than those raised by local-to-regional scale water resource management indicators. The continental-to-global perspective could, for example, highlight the importance of the water cycle of the Amazon rainforest for climate change (D'Almeida et al., 2007; Miguez-Macho & Fan, 2012), monsoon system, and agricultural production outside the region through teleconnections and indirect impacts (Nobre, 2014). This could lead to the recognition of the global community's role as stakeholder in the Amazon rainforest water cycle beyond the regional and national scale.

An additional motivation of the scientific and ethical grand challenge of the water planetary boundary is the numerous Earth System and socio-hydrologic research questions (that we raise but do not answer here) which require the application of serious and sustained attention to the water planetary boundary (Ziegler et al., 2017):

- 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?
- What water-related changes may lead to supraregional or global tipping points related to critical water and Earth System functions? To what changes, and in what regions, is the Earth System particularly vulnerable?
- How do we manage tradeoffs between global development (e.g. the Sustainable Development Goals) and increasing pressure on global water resources?
- How do existing water governance mechanisms and institutions respond to and influence global water cycling?

1.3 Objectives, scope and terminology

Our objective is interrogating and reframing the water planetary boundary to reflect complex, interconnected and heterogeneous freshwater processes in the Earth System. This work is based on multiple workshops, working groups and intense collaboration and debate. First, we review how the planetary boundaries are defined and identified (Box 1) and highlight the core functions of freshwater in the Earth System (Box 2). Based on this, we develop a framework for evaluating the current freshwater use planetary boundary (Section 2) and establish a new set of sub-boundaries representing different functions of the water cycle (Section 3). Instead of presenting a new quantitative water planetary boundary, our goal is to provide a scientific roadmap for the Grand Challenge of redefining an operable planetary boundary of water. By holistically and transparently evaluating the value, concerns, and possibilities of water planetary boundaries, we aim to move the debate forward, in response to recent discussions (Gerten et al., 2015a; Heistermann, 2017; Jaramillo & Destouni, 2015; Rockström, 2017; Sivapalan, M., 2017).

Since planetary boundaries and water in the Earth System are broad and interdisciplinary topics, we narrow our scope to focus on terrestrial freshwater, while acknowledging the vital role of oceans; for clarity ‘water’ refers herein to terrestrial freshwater. We also focus on water quantity (stores and fluxes) rather than water quality and temperature, again acknowledging the importance of both, in part since streamflow is often considered a reasonable proxy for aquatic ecological integrity (Richter et al., 2003). Marine systems and water quality and temperature are related to other planetary boundaries such as ocean acidification, biogeochemical flows, climate change, and novel entities. An important terminology note is that we argue that the original planetary boundary for water defined as ‘freshwater use´ should be replaced with the more holistic planetary boundary on ´water´ or ‘water planetary sub-boundaries’. We use the term ‘freshwater use planetary boundary’ only to refer to the current definition presented in Rockström et al., (2009a,b), Gerten et al. (2013) and Steffen et al. (2015).

Box 1. Introduction to planetary boundaries and safe operating space (text for each box shown in dark grey, to maintain line numbering)

Planetary boundaries are defined as biogeophysical boundaries at the planetary scale for the processes and systems, which together regulate the state of the Earth System. The planetary boundaries place scientifically defined guardrails for human perturbations that collectively delimit the ‘safe operating space for humanity’ to enable continued world development on planet Earth that remains in a manageable Holocene-like inter-glacial state (Figure 2); 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).

Nine planetary boundary processes and systems have been identified. For each boundary process/system, a control variable (Table 1) is defined, where the Earth System response variable moves the Earth away from Holocene conditions (i.e. the past 11,700 years), that have led to the development and proliferation of human societies. The boundaries for biosphere integrity and biogeochemical flows are subdivided with different control variables covering different aspects of the Earth System response to anthropogenic perturbation. For the planetary boundaries climate change and ozone depletion, identifying and quantifying control variables is relatively easy, as they are well-mixed global systems, moreover with a single dominant human driver (ozone depleting substances and greenhouse gases). In other words, since the eventual effect on climate or the ozone layer is independent of where in the world the CO_2 or ozone-depleting substances are emitted, respectively, these boundaries can straightforwardly be assessed in a 'top-down' manner.

Boundaries for land-system change, biosphere integrity and freshwater use cannot be directly connected to a single, well-mixed global driver or indicator; the eventual effects on the Earth System depend on the kinds, rates, locations and sequencing of processes, some of which have critical transitions, that happen at local or regional scales. These boundaries therefore represent regulatory processes that provide the underlying resilience of the Earth System (Rockström et al., 2009a). If sufficiently widespread, however, human-caused perturbations to these 'bottom-up' processes will have significant aggregate consequences at global scale, with systemic or cascading interactions with other boundaries (Galaz et al., 2012).

Over geological time, the state of the Earth System is defined in terms of well-defined shifts as well as slower, gradual co-evolution of the climate system and the biosphere. Steffen et al. (2015) thus suggest that climate change and biosphere integrity should be considered 'core' planetary boundaries. Changes in either of these boundaries themselves have the ability to drive the Earth System into a new state, away from Holocene conditions (i.e. the past 11,700 years) that have allowed the development and proliferation of human societies. The other boundaries, including water, have Earth System effects by operating through the two core boundaries. In simple terms, the dynamics and state of the planetary boundaries for water, land, ocean acidification, novel entities, and biogeochemical flows (N and P cycle perturbation), will contribute to the final outcome of the climate and biosphere integrity boundaries, which thus constitute the aggregate manifestation of the interactions among all the other boundaries. Given the natural variability of Earth System dynamics, the limitations of large-scale environmental monitoring and modelling, and fundamental scientific uncertainty about complex system behaviour at all scales up to the global, the planetary boundary positions are not equivalent to any specific threshold values in the control variables. Rather, the rationale is that planetary boundaries should be placed at a 'safe' distance from potential critical thresholds or other, more gradual detrimental developments. The planetary boundaries framework resolves this challenge by focusing on defining the scientific range of uncertainty for each boundary definition (e.g., a range of 350-450 ppm CO_2 for the planetary boundary on climate change). Here there are no normative judgements, only an attempt to carry out the best possible scientific assessment, and disclose clearly the range of uncertainty. Then follows a normative step, where the planetary boundaries framework, adopting a precautionary principle (based on the extraordinary complexity of the functioning of the Earth System and in particular inter-actions and feedbacks among Earth System processes) by placing the planetary boundary position at the lower (careful) end of the uncertainty range for each control variable (350 ppm CO_2 for climate change). The safe operating space for humanity on Earth is thereby set at the lower end of the uncertainty range. When transgressing this boundary, humanity enters a 'danger zone', constituted by the uncertainty range (a zone when abrupt and irreversible changes can occur, but scientifically we cannot be certain). The upper range of the uncertainty range is the 'high-risk' zone in terms of the scientific assessment of risks to trigger non-linear irreversible changes that can destabilise the state of the Earth System and/or fundamentally change the ability of the Earth System to support human development. The final adoption of planetary boundaries, therefore, involves normative judgements of how societies choose to deal with risks and uncertainties of global environmental change (Rockström et al. 2009a,b; Galaz et al. 2012). The planetary boundaries have been combined with social boundaries (based on the Sustainable Development Goals), together defining a 'safe and just operating space' for humanity (Raworth, 2017).

INSERT Figure 2 here

2. Interrogating the current freshwater use planetary boundary

We propose a qualitative evaluation framework with seven criteria for defining a useful water planetary boundary based on the definition and purpose of the planetary boundaries introduced in Box 1. This framework could be used for other planetary boundaries in the future and significantly clarifies and expands on the set of criteria proposed by Rockström et al. (2009a) for identifying useful control variables for planetary boundaries: (i) the variable is universally applicable for the sub-systems linked to that boundary, (ii) it can function as a robust indicator of process change, and (iii) there are available and reliable data.

Scientific criteria

1) Planetary boundary variables: Are the proposed control and response variables clearly defined and related? Is there a clear basis for a planetary boundary value?
2) Regional impacts and upscaling mechanisms: Is there evidence for regional impacts, and plausible mechanisms by which regional impacts could scale to global impacts?
3) Impacts on Earth System stability: Is there evidence that this process impacts Earth's stability, directly or indirectly through interactions with core planetary boundaries?

Scientific representation criteria:

4) Measurable: Can the status of the control variable be measured, tracked in time, and monitored?
5) Understandable and operational: Is the planetary boundary broadly understandable to non-scientific audiences and potentially operational?
6) Represents regional and global impacts: Does this planetary boundary represent both regional and global impacts? Is this representation consistent with the social perceptions of impacts?
7) Uniqueness: Are the processes or impacts uniquely represented by this planetary boundary, or is there overlap and redundancy with other planetary boundaries?

Criteria 1–3 are fundamental requirements of any planetary boundary, as they address scientific evidence of mechanisms, especially relating to Earth's 'Holocene-like' state. Criteria 4) and 5) are necessary for operationalisation and criteria 6) and 7) address the usefulness of a planetary boundary by ensuring that representation of impacts can resonate with social concerns and policy prioritizations and that redundancy in the planetary boundary framework is limited. We evaluated the already proposed planetary boundaries for water based on these criteria and find that none of them fully meet any of the evaluation criteria (Table 2; see Appendix for more detail). We thus suggest replacing the current planetary boundary for freshwater using the roadmap we outline below, focusing on Earth System functions of water instead of water quantity.

3. A road map for reframing the water planetary boundary

3.1 Dividing the current planetary boundary into planetary sub-boundaries

The water planetary boundary must be subdivided to more realistically represent the complexity and heterogeneity of the water cycle and how it interacts with the various components of the Earth System (Figure 1c) at various time and space scales (Figure S1). We suggest subdivision based on water stores: atmospheric water, surface water, soil moisture, groundwater and frozen water. This approach is physically based and could directly use hydrologic models and data, making it more measurable as well as understandable to hydrologists and non-hydrologists (Table 2). By dividing the water cycle into these five stores, we do not imply that different stores do not interact, as illustrated in Figure 1b. An alternative division, based on the Earth System functions of water (hydroclimatic regulation, hydroecological regulation, storage, and transport) would represent the core functions directly, but it adds complexity, as different components of the Earth System may have the same core function (i.e. hydroclimatic regulation through albedo control by clouds, glaciers, and inland surface waters).

We propose six planetary sub-boundaries for water based on the five water stores (Figure 3). For each store, we considered the most important processes that met the largest number of evaluation criteria (Section 2) and most holistic representation of the crucial functions of water in the Earth System (Box 2). We argue that combining these sub-boundaries is not appropriate because these stores operate at different spatiotemporal scales and are important to different Earth System components. This means we have opted to include two planetary sub-boundaries for atmospheric water to incorporate both its hydroclimatic (evapotranspiration regulating climate) and hydroecological (precipitation supporting biodiversity) functions. The Earth System function and **process (in bold)** addressed by each of the proposed sub-boundaries are highlighted in Figure 3 and summarized below:

- atmospheric water (hydroclimatic regulation) focuses on **evapotranspiration** that is important to climate pattern stability or land-atmosphere coupling stability;
- atmospheric water (hydroecologic regulation) focuses on **precipitation** that maintains biomes which is connected to biodiversity;
- soil moisture focuses on **carbon uptake** or net primary productivity;
- surface water focuses on **streamflow** and related habitat that maintains aquatic biodiversity;
- groundwater focuses on **baseflow** or **sea level rise** that are important to aquatic biodiversity or the oceans, respectively;
- frozen water focuses on **ice sheet** volume which is important to sea level rise in the oceans.

Possible control variables and suggested response variables are compiled in Figure 3. Their suitability as planetary sub-boundaries needs to be tested by plotting the relationships between the variables as in Figure 2. The horizontal axis of Figure 2 shows the control variable, which represents local processes aggregated to planetary-scale. This necessitates an aggregation methodology, which we discuss below. The vertical axis of Figure 2 shows the response variable, which can also be thought of as global impacts mediated through water. For example, the ‘surface water’ component may have global impacts on ‘biodiversity’ through the ‘hydroecological regulation’ function, specifically the processes of ‘streamflow and habitat provision’.

Our preliminary evaluation of the six possible future planetary sub-boundaries for water (Table S1) shows that they are more measurable, understandable, operational and potentially represent both regional and global impacts. However, they require refinement through extensive community efforts because, while there is generally strong evidence of regional impacts, robustness of upscaling mechanisms and impacts on Earth System stability are variable (Box 3). The new sub-boundaries overlap with each other and with other planetary boundaries because of complex interactions and feedbacks within the water cycle (see Appendix for more details on overlaps).

INSERT FIGURE 3 HERE

Box 2. The Earth System functions of water: the scientific foundation of a water planetary boundary

The water cycle or hydrosphere is a complex system with different stores interacting with varying strengths and over a wide range of scales (Figure S1) 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; Qiuhong Tang & Taikan Oki, 2016; UNESCO, 1978) here we highlight four identified core *Earth System functions of water*: hydroclimatic regulation, hydroecological regulation, storage and transport. Inevitably, this description and related citations are non-exhaustive, and serve primarily to outline a scientific foundation for the water planetary boundary (Gerten, 2013). Table 1 indicates how these functions are different than *watershed functions* (Black, 1997; Wagener et al., 2007) and *water functions for social-ecological resilience* in the Anthropocene (Falkenmark et al., 2019).

Hydroclimatic regulation: Water exchange between 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 regarded as the most effective 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 vapour is also an important heat-transport vehicle as it transports and redistributes heat across the globe (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 as a key variable of climate, is influenced by evaporation 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).

Hydroecological regulation: Overall, water's hydroecological function enables and connects life on land and in aquatic ecosystems, and creates and sustains the ecosystems that human societies depend on. This hydroecological function can be described by the quantity of water present at different times within the year relative to the 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 water's hydroclimatic functions, since almost all water stored on land has an atmospheric origin, and water's storage function, since surface water bodies harbor aquatic ecosystems and groundwater stores buffer 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. 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., 2014a), 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 and providing water for irrigated agriculture (Dalin et al., 2017; Richey et al., 2015). 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 soil particles, nutrients and chemicals on the surface or within soils (Earle et al., 2015). 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. Transportation of sediments forms many types of sedimentary rocks, which contribute to the geologic record of Earth history (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). 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 biodiversity and the hydrological environment (Smith & Schindler, 2009). It is important to note that we include 'transport' here to holistically consider Earth System functions of water but we do not deal with it explicitly in our sub-boundaries since it is primarily related to water quality.

3.2 Methodological questions of scale, data and norms

To set new planetary sub-boundaries, a number of methodological issues must be addressed. First are questions of space and time scales to consider in analysis. Figure 3c summarizes spatial aggregation appropriate for each water planetary sub-boundary. For example, the surface water and groundwater sub-boundaries could be analyzed at the large basin and regional aquifer scale, respectively. For time scale, the planetary boundary concept 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 consistently 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 against which current or future conditions may be compared, understanding that this does not include all anthropogenic disturbances.

Second, a useful planetary boundary will be model-agnostic but does require some uniformity in modeling approach. We argue that the appropriate approach requires explicit accounting of climate feedbacks, impacts on aquatic and terrestrial biodiversity, and other coupled impacts in order to test relationships between control and response variables. Most existing global hydrologic models have only limited ability to do so (Bierkens, 2015; Sood & Smakhtin, 2015). For example, the previous analysis of the water planetary boundary (Steffen et al., 2015b) used an offline simulation (i.e., not dynamically coupled to a general circulation model) of a dynamic global vegetation model to evaluate environmental flow requirements and human impact on them. It is likely that adequately assessing planetary boundaries 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.

Third, planetary boundaries are inherently normative in terms of the level of risk humanity is willing to take, so setting boundaries requires approaches beyond standard hydrologic methods. An evaluative standard designates some actions or outcomes as good, desirable or permissible; a normative question asks “what should be” (a subjective condition) instead of asking “how much” (an objective fact) or “what is” (an objective condition). Informally, a normative approach to the water planetary boundary would for example ask “what risks associated with water cycle modifications do we want to avoid?” At present, determining a normative standard remains a significant challenge to identifying planetary sub-boundaries for water. There has never been cohesive global water governance to set or inform normative standards of this kind, although it is possible. Water governance increasingly addresses global issues, and global water initiatives have proliferated 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.

3.3 Quantifying control and response variables

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 resilience loss caused by water impacts in one place can remediated by water abundance in another place. We therefore propose four new methods (Figure 4) for quantifying control variables to replace the current methodology:

1) ‘Hydrologic unit approach’ - calculates the percentage of global land that has crossed a certain threshold using a defined scale of analysis (Figure 3). For example, for the streamflow sub-boundary, the control variable could be the percentage global land area of basins (or percentage length of river network to not bias by river length) not meeting environmental flow requirements; the scale of analysis are basins or river networks. This approach would be useful if widespread degradation of conditions or change of fluxes or stores leads to significant change in the response variable. High latitude regions which are not included in most hydrologic models would be excluded, except for frozen water stores.
2) ‘Weighted hydrologic unit approach’ - calculates the percentage of the global land area that has crossed a certain threshold *weighted by the importance of that hydrologic unit to Earth System function* (also at a defined scale of analysis). For example, again for the streamflow sub-boundary, the control variable could be the percentage 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.

3) ‘Rate of change approach’ - calculates the percentage of the global land mass experiencing rapid change (also at a defined scale of analysis). For example, for the streamflow sub-boundary, the control variable could be the global percentage of river network where streamflow is rapidly changing. This approach implies that the rate of change is more important than absolute magnitude of change, which could be useful for identifying global-scale thresholds.
4) 'Keystone region approach’ - identifies regions where certain water stores are disproportionately important to specific Earth System components. This approach 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) may have a disproportionately important impact on the stability of the Earth System (see definition of keystone region in Table 1) and propose keystone regions be identified by (1) risk of critical transition imposed by human interference, (2) risk and magnitude of cascading impacts on other systems or regions following a critical transition, or (3) risk and magnitude of cascading impacts on other systems and regions following human interference even in the absence of a critical transition. The current state of knowledge of important regions, critical regional transitions and cascading impacts is reviewed in Box 3.

Different methods may be more effective or appropriate for each of the water planetary sub-boundaries. An argument for the rate of change approach, for example, is that the rate and time scale of environmental change may be more important to social adaptation than absolute thresholds. Using streamflow as an example, societies thrive in regions with a wide range of streamflow rates, but rapid change in streamflow could be problematic. The ‘keystone region approach’ and the ‘weighted hydrologic region approach’ both identify regions that are disproportionately important to a response variable, but the ‘keystone region approach’ focuses on regional case studies whereas the ‘weighted hydrologic region approach’ focuses on spatially weighted global data. 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).

INSERT FIGURE 4 HERE

3.4 Setting 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 normative 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 (Figure 4). In other words, these are the water boundaries that would arise if global carbon governance actors considered water impacts.

3.5 Using the water planetary sub-boundaries

For the water planetary boundary to have practical value for water management, it needs to be operational and informative at the sub-global scales at which water is managed such as basins, individual nations (Cole et al., 2014b; Dao et al., 2015; Lucas & Wilting, 2018), areas governed by multinational organizations (Häyhä et al., 2018b), or the footprint of a company's supply chain (Clift et al., 2017b). Here, we briefly introduce how the water planetary boundary may be used at sub-global scales, which is the focus of a separate study (Zipper et al., in prep). Previous attempts at operationalizing the planetary boundaries have largely focused on calculating a country's 'fair share' of the global safe operating space, (Figure 2). (Häyhä et al., 2016b) identify three key dimensions to consider: (1) biophysical processes, which define the relevant scale at which the planetary boundary can be addressed; water cycle processes are spatially heterogeneous so the global impacts of a change depend on site-specific factors; (2) socio-economic considerations, which define the environmental impact a country has both inside and outside of its borders (MacDonald et al., 2015); global accounting methods such as the water footprint (Hoekstra & Mekonnen, 2012) are tools for addressing this dimension although regional opportunity costs need to be considered (Kahil et al., 2018); and (3) ethical considerations, which address difference among countries in environmental impacts caused by exceeding the control variable as well as their ability to respond to environmental challenges; equity-based allocation frameworks could address this dimension.

In addition to methods for calculating sub-global fair shares, the water planetary boundary can be operationalized at sub-global levels using the same methods employed to define the global boundaries. For instance, if the global surface water sub-boundary is defined based on the proportion of large basins meeting environmental flow requirements (Table 3), a national or regional surface water sub-boundary could be calculated based on the proportion of basins within that area meeting environmental flow requirements. In this manner, a regional safe operating space could be defined that is scientifically consistent with the global methodology (Dearing et al., 2014). At a regional level, the domain of analysis may differ depending on the sub-boundary considered; for instance, the surface water sub-boundary may require considering all basins within or draining into a region, while the atmospheric water sub-boundary would require considering the region's precipitationshed (Keys et al., 2012).

Box 3. Possible keystone regions, critical regional transitions and cascading impacts

This overview highlights the existence and also the limitations of current knowledge of possible keystone regions, critical regional transitions and cascading impacts. It is intended to highlight key knowledge gaps that are essential to examine in the process of assessing and identifying potential planetary sub-boundaries for water. The water stores are discussed in counter-clockwise order in Figure 1c starting with atmospheric water, while acknowledging that water stores are intimately and inherently interlinked, so discussing 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 (precipitation): The Amazon rainforest is a known keystone region with multiple alternative stable states primarily governed by precipitation. 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 among others precipitation, fire feedback, and ecosystem response (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 keystone 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 and amount are also know 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).

Atmospheric water (evapotranspiration): 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 land-ocean temperature gradient, studies have also shown that evaporation (i.e., latent heat) on land can affect the monsoon. For example, Tuinenburg (2013) showed that the onset of Indian summer monsoon is delayed by irrigation evapotranspiration, Nogherotto et al. (2013) showed that decreased evaporation over deforested area in the Congo has a seasonal influence on the strength of the West and south-equatorial African monsoon, and (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 dryland 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). 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 effect 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 organics 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 clear 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 but as described above water quality is considered in the biogeochemical flows planetary boundary.

Wetland ecosystems may be considered keystone regions due to their richness in water-dependent biodiversity coupled with the multifaceted role they play 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).

For the perennial-ephemeral and oligotrophic-eutrophic tipping points, 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, surface water flows from keystone terrestrial regions can affect Earth System processes due to their natural freshwater, sediment and nutrient delivery to coastal zones and the ocean. Reductions in these flows 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). 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).

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 ephemeral (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, keystone groundwater-dependent ecosystems which may contribute to regional-scale shifts could be identified as those regions suggested to be keystone evapotranspiration regions (see above) and have shallow groundwater. For instance, groundwater is an essential contributor to evapotranspiration in the Amazon basin (Fang et al., 2017; Miguez-Macho & Fan, 2012).

Frozen water: Unlike the other water sub-boundaries, critical transitions associated with frozen water storage have been studied extensively due to their potential contributions to global sea level rise. While mass loss due to ice melt is widespread and accelerating in both the Antarctic and Greenland ice sheets (Velicogna et al., 2014b), 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).

4. Concluding with an invitation to a Grand Challenge

To transparently evaluate the value, concerns and possibilities for the water planetary boundary, we interrogated and reframed it to more holistically account for the complexity and heterogeneity of water and other Earth System components. Our examination of water planetary boundaries has led to the following conclusions**:**

1) The planetary boundary framework could complement existing tools for water resource management by offering a unique approach for assessing water cycle modifications as part of the wider human impact on the Earth System (Section 1.2). Thus, despite the well-founded criticism of the current freshwater use planetary boundary (Section 2), we argue that the concept of a planetary boundary for water is useful and worth serious intellectual attention.
2) Planetary boundaries can and should be evaluated with qualitative and quantitative analysis, and iteratively updated as science (for the biophysical aspects) and society (for the normative aspects) evolve. We developed a framework for evaluating water planetary boundaries (Section 2) that could be used to evaluate other planetary boundaries as well, especially those that do not have clear global tipping points - such as land use or biodiversity loss - and whose critical transitions start at the regional and local scales.
3) 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 other 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. We reviewed and synthesized the core functions of water in the Earth System (Box 1) and how these relate to the Earth System functions underlying other planetary boundaries (Figure 3).

4) The current water planetary boundary does not adequately represent the complex and interconnected nature of water, and thus it should be replaced. We developed a roadmap for reframing the planetary boundary for water with new sub-boundaries for each water component. This encompasses new modeling and analysis and much work in clarifying tipping points, keystone regions, cross-scale propagation of impacts, and the fundamental relationship between core Earth System functions of water and other Earth System components. We suggest that interim planetary sub-boundaries be set while working in parallel towards fully elaborated planetary sub-boundaries.

We invite the hydrology and water resource community to apply serious and sustained attention toward the water planetary boundary, which could be transformative to our understanding of socio-hydrologic systems across scales, up to the global (Section 1.2). We suggest three initiatives that can be tackled immediately and simultaneously (Figure 4) by highly collaborative working groups from diverse backgrounds:

- Initiative 1 could compare the ‘weighted hydrologic unit’ approach to the ‘keystone 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’ approach, 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 as outlined in the ‘Goal’ and ‘Using the water planetary sub-boundaries’ sections of Figure 4. We therefore end with an invitation to the hydrology and water resource community to join us in following this Grand Challenge roadmap, 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.

ACKNOWLEDGEMENTS

This community project was directly supported by a STINT internationalization grant to TG and IF. We thank many members of the community who contributed to the discussions. We have no conflicts of interest and no data is used in this manuscript.

APPENDIX

Summary of previous critiques of the current planetary boundaries for freshwater use

Earlier discussions have criticised the definition of the freshwater use boundary for a number of reasons including: 1) scale – water problems are often considered only at local to regional scales, whereas the metric is global which some consider misleading (Heistermann, 2017); 2) aggregation - currently sums streamflow fluxes but the best way to summarize diverse local impacts to a global metric is not clear (Heistermann, 2017); 3) control variable – blue water use is not a biophysical variable representing the complexity of the water cycle (Jaramillo and Destouni, 2015a); 4) mechanism – there is limited evidence of tipping points or connections between water use and processes that would lead to the Earth leaving a Holocene-like state (Heistermann, 2017); 5) underestimation of water use – the global consumptive use of freshwater may be larger due to possible additional or larger effects from irrigation and flow regulation (Jaramillo and Destouni, 2015b; but see (Gerten et al., 2015b); and 6) the planetary boundary may actually be lower as the current global aggregate tends to disregard conditions of local overuse of water resources and may provoke the thought that all usable water can be accessed (Molden, 2009). The present lack of uptake and the range of published criticisms raise the fundamental question of the relevance or value of a water planetary boundary for water management, and for environmental governance more broadly.

Detailed interrogation of the current planetary boundaries for freshwater use

First, while Rockström et al. (2009a, 2009b) and Gerten et al. (2013) both defined control variable limits, neither clearly defined the response variable, nor the relationship between control and response variables.

Second, while the impacts of water consumption on water systems at regional scales are clear and well documented, studies on the plausible mechanisms how regional impacts could scale to global impacts are generally scarce. Basins are nested, and the impacts of water use are scale-dependent, which is obscured by the current water planetary boundary methodology. For example, water use in a small basin may cause stress at the scale of that basin, but the small basin may be nested within a larger one that is on average not stressed. The same logic applies to environmental flows: water use in a small basin or along a certain river stretch may cause a transgression of environmental flow limits at that scale, but the small area may be nested within a larger basin with flows above the environmental flow limits.

Third, consumptive blue water use does not fully capture water's complex interactions with other major Earth System components (Box 1), and there is scarce evidence that water use on its own can destabilize the Earth System. While multiple, simultaneously occurring regional environmental flow transgressions could potentially contribute to the transgression of the biosphere integrity planetary boundary and thus indirectly impact Earth System stability, a simple aggregate of water consumption across all regions and river basins cannot adequately represent the underlying mechanisms. Even when considering environmental flow transgressions in a spatially explicit manner (Gerten et al. 2013 and the basin scale boundary of Steffen et al. 2015), it is unclear whether transgressions in all basins should be treated equally or if some regions contribute disproportionately to maintaining biosphere integrity.

Fourth, while one argument for the current water planetary boundary might be a control variable that is simple, measurable and understandable, consumptive blue water use is in fact notoriously challenging to estimate due to uncertainty in statistics of water withdrawals (Vörösmarty et al., 2000). Furthermore, different approaches to quantify consumptive blue water use tend to produce conflicting estimates (e.g., Hoekstra and Mekonnen, 2012; Siebert and Döll, 2010; Rost et al., 2008;

Jaramillo and Destouni, 2015b) and separating anthropogenic blue and green consumptive use from natural fluxes requires complex water resource modeling. Additionally, there has been significant debate on what to include in and how to perform calculations of consumptive water use. For instance, Jaramillo & Destouni (2015a) propose that green water and its human-driven changes should be taken into account directly, and that doing so would lead to the planetary boundary for freshwater use already being transgressed. While Rockström et al. note the crucial importance of green water flows for ecosystems in the original planetary boundary papers (2009a, 2009b), it is not reflected in the proposed control variable in a meaningful quantitative way.

Fifth, consumptive water use was originally suggested as a surrogate/proxy variable intended to capture human modification to the hydrological cycle. However, this subtle but crucial notion has escaped many readers – proponents and critics alike – prompting arguments against a global cap on consumptive blue water use. For example, it has been suggested that a water planetary boundary may be counterproductive as it suggests that increased water use in one location can be offset by a decrease in water use elsewhere, even if there is no biophysical connection between the two locations (Heistermann, 2017). Another frequent criticism of the water planetary boundary is that there is no global water management board or entity nor is one likely in the foreseeable future, so a firm global boundary may not have practical meaning for global water management. Thus, for the revised planetary boundary to have any practical value for water management, it will be necessary to apply it at sub-global scales. Such down-scaled global boundaries should not supersede management thresholds based on local conditions, but rather provide a framework for determining whether regional water management is consistent with global boundaries and an aspirational goal for local managers.

Finally, it is important to explicitly consider the other aspects of scientific representation of the current water planetary boundary. Ideally, a water planetary boundary would represent both global and regional impacts of modifications to the hydrological cycle, and be consistent with the social perception of water problems. The current global aggregate metrics (Rockström et al., 2009a,b; Gerten et al., 2013) largely fail to represent the inherently local nature of water problems and provide only a partial perspective. The water use boundaries have some overlap with other planetary boundaries, especially that for land-system change, which is often associated with changes in both green and blue water fluxes, highlighting the fact that boundaries interact but also suggesting some redundancy in current planetary boundary definitions.

Additional description of overlap between sub-boundaries

Overlap with planetary boundaries of climate change and biosphere integrity is expected, as these are suggested to be the ‘core’ boundaries through which the others operate (see section 1; Steffen et al. 2015). Similarly, some degree of overlap with other sub-boundaries is inevitable because of the complex interactions and feedbacks within the water cycle. The sub-boundaries for evapotranspiration and soil moisture further overlap with the land-system change boundary, which also focuses on climate-regulating processes in land systems but, we argue, does not adequately represent the hydroclimate function covered by our proposed sub-boundaries.

Additional justification and description of interim sub-boundary

The discussions and decision-making of climate change agreements, such as the Paris agreement are based in part on impacts to water systems. For example, water security, floods, droughts are often significant considerations in the IPCC reports.

For calculating the interim sub-boundaries we specifically suggest using existing global hydrologic models and the ‘hydrologic unit approach’ described above to quantify the change of each proposed control variable from ~1950 to an end-of-century (~2100) scenario considering climate, land and water use change. The Paris target of 2°C or less corresponds to RCP 4.5, which does not project global temperature change stabilization until around 2100 (USGCRP 2018). Thus, 2100 provides a reasonable time frame for making modeling comparisons between Holocene and Anthropocene conditions for the six water sub-boundaries. For example, for the planetary sub-boundary for surface water, the control variable could be the 'percentage area of large basins within environmental flows' from early 1900s to ~2100s. By using models representing climate change, land use and water use, we would be looking at the combined impact of each of these on the different water stores. To pragmatically simplify identifying these interim planetary boundaries, we suggest not attempting to identify keystone regions or the functional relationships between control and response variables as described above. It is important to note that these interim sub-boundaries do not necessarily use the precautionary principle since interim sub-boundaries may be larger or smaller than the planetary boundaries defined using the relationship between control and response variables.

References

Abraham, J. P., Baringer, M., Bindoff, N. L., Boyer, T., Cheng, L. J., Church, J. A., … Willis, J. K. (2013). A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. *Reviews of Geophysics*, *51*(3), 450–483. https://doi.org/10.1002/rog.20022

Acreman, M. C., Overton, I. C., King, J., Wood, P. J., Cowx, I. G., Dunbar, M. J., … Young, W. J. (2014). The changing role of ecohydrological science in guiding environmental flows. *Hydrological Sciences Journal*, *59*(3–4), 433–450. https://doi.org/10.1080/02626667.2014.886019

Alcamo, J., Flörke, M., & Märker, M. (2007). Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrological Sciences Journal*, *52*(2), 247–275.

Barreto, M. B. (2008). Diagnostics About the State of Mangroves in Venezuela: Case Studies from the National Park Morrocoy and Wildlife Refuge Cuare. In P. H. Lieth, D. M. G. Sucre, & B. Herzog (Eds.), *Mangroves and Halophytes: Restoration and Utilisation* (pp. 51–64). Springer Netherlands. https://doi.org/10.1007/978-1-4020-6720-4_6

Bathiany, S., Notz, D., Mauritsen, T., Raedel, G., & Brovkin, V. (2016). On the Potential for Abrupt Arctic Winter Sea Ice Loss. *Journal of Climate*, *29*(7), 2703–2719. https://doi.org/10.1175/JCLI-D-15-0466.1

Bell, J. P., Tompkins, A. M., Bouka-Biona, C., & Sanda, I. S. (2015). A process-based investigation into the impact of the Congo basin deforestation on surface climate. *Journal of Geophysical Research*, *120*(12), 5721–5739. https://doi.org/10.1002/2014JD022586

Belmont, P., & Foufoula-Georgiou, E. (2017). Solving water quality problems in agricultural landscapes: New approaches for these nonlinear, multiprocess, multiscale systems. *Water Resources Research*, *53*(4), 2585–2590. https://doi.org/10.1002/2017WR020839

Bestelmeyer, B. T., Williamson, J. C., Archer, S. R., Sayre, N. F., Duniway, M. C., Okin, G. S., & Herrick, J. E. (2015). Desertification, land use, and the transformation of global drylands. *Frontiers in Ecology and the Environment*, *13*(1), 28–36. https://doi.org/10.1890/140162

Biddanda, B. A. (2017). Global significance of the changing freshwater carbon cycle. *Eos*, *98*. https://doi.org/10.1029/2017EO069751

Bierkens, M. F. P. (2015). Global hydrology 2015: State, trends, and directions. *Water Resources Research*, *51*(7), 4923–4947. https://doi.org/10.1002/2015WR017173

Biermann, F., Abbott, K., Andresen, S., Bäckstrand, K., Bernstein, S., Betsill, M. M., … Folke, C. (2012). Navigating the Anthropocene: improving earth system governance. *Science*, *335*(6074), 1306–1307.

Black, P. E. (1997). Watershed functions. *JAWRA Journal of the American Water Resources Association*, *33*(1), 1–11.

Boers, N., Marwan, N., Barbosa, H. M. J., & Kurths, J. (2017). A deforestation-induced tipping point for the South American monsoon system. *Scientific Reports*, *7*, 41489. https://doi.org/10.1038/srep41489

Bogan, M. T., & Lytle, D. A. (2011). Severe drought drives novel community trajectories in desert stream pools. *Freshwater Biology*, *56*(10), 2070–2081. https://doi.org/10.1111/j.1365-2427.2011.02638.x

Booth, E. G., Zipper, S. C., Loheide, S. P., & Kucharik, C. J. (2016). Is groundwater recharge always serving us well? Water supply provisioning, crop production, and flood attenuation in conflict in Wisconsin, USA. *Ecosystem Services*, *21*, *Part A*, 153–165. https://doi.org/10.1016/j.ecoser.2016.08.007

Booth, E. G., & Loheide, S. P. (2012). Comparing surface effective saturation and depth-to-water-level as predictors of plant composition in a restored riparian wetland. *Ecohydrology*, *5*(5), 637–647. https://doi.org/10.1002/eco.250

Brauman, K. A., Richter, B. D., Postel, S., Malsy, M., & Flörke, M. (2016). Water depletion: An improved metric for incorporating seasonal and dry-year water scarcity into water risk assessments. *Elem Sci Anth*, *4*.

Bring, A., Fedorova, I., Dibike, Y., Hinzman, L., Mard, J., Mernild, S. H., … Woo, M.-K. (2016). Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. *Journal of Geophysical Research-Biogeosciences*, *121*(3), 621–649. https://doi.org/10.1002/2015JG003131

Brown, J., Bach, L., Aldous, A., Wyers, A., & DeGagné, J. (2011). Groundwater-dependent ecosystems in Oregon: an assessment of their distribution and associated threats. *Frontiers in Ecology and the Environment*, *9*(2), 97–102. https://doi.org/10.1890/090108

Campbell, B., Beare, D., Bennett, E., Hall-Spencer, J., Ingram, J., Jaramillo, F., … Shindell, D. (2017). Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society*, *22*(4). https://doi.org/10.5751/ES-09595-220408

Carlisle, D. M., Grantham, T. E., Eng, K., & Wolock, D. M. (2017). Biological relevance of streamflow metrics: regional and national perspectives. *Freshwater Science*, *36*(4), 927–940. https://doi.org/10.1086/694913

Catford, J. A., Morris, W. K., Vesk, P. A., Gippel, C. J., & Downes, B. J. (2014). Species and environmental characteristics point to flow regulation and drought as drivers of riparian plant invasion. *Diversity and Distributions*, *20*(9), 1084–1096. https://doi.org/10.1111/ddi.12225

Chasmer, L., & Hopkinson, C. (2017). Threshold loss of discontinuous permafrost and landscape evolution. *Global Change Biology*, *23*(7), 2672–2686. https://doi.org/10.1111/gcb.13537

Cherlet, M., Hutchinson, C., Reynolds, J., Hill, J., Sommer, S., & von Maltitz, G. (Eds). (2018). *World Atlas of Desertification*. Luxemburg: Publication Office of the European Union.

Chipman, M. L., & Hu, F. S. (2017). Linkages Among Climate, Fire, and Thermoerosion in Alaskan Tundra Over the Past Three Millennia. *Journal of Geophysical Research: Biogeosciences*, *122*(12), 3362–3377. https://doi.org/10.1002/2017JG004027

Cintron, G., Lugo, A. E., Pool, D. J., & Morris, G. (1978). Mangroves of Arid Environments in Puerto Rico and Adjacent Islands. *Biotropica*, *10*(2), 110–121. https://doi.org/10.2307/2388013

Clarke, C. J., George, R. J., Bell, R. W., & Hatton, T. J. (2002). Dryland salinity in south-western Australia: its origins, remedies, and future research directions. *Soil Research*, *40*(1), 93–113.

Clift, R., Sim, S., King, H., Chenoweth, J. L., Christie, I., Clavreul, J., … Murphy, R. (2017a). The Challenges of Applying Planetary Boundaries as a Basis for Strategic Decision-Making in Companies with Global Supply Chains. *Sustainability*, *9*(2), 279. https://doi.org/10.3390/su9020279

Clift, R., Sim, S., King, H., Chenoweth, J. L., Christie, I., Clavreul, J., … Murphy, R. (2017b). The Challenges of Applying Planetary Boundaries as a Basis for Strategic Decision-Making in Companies with Global Supply Chains. *Sustainability*, *9*(2), 279. https://doi.org/10.3390/su9020279

Cole, M. J., Bailey, R. M., & New, M. G. (2014a). Tracking sustainable development with a national barometer for South Africa using a downscaled “safe and just space” framework. *Proceedings of the National Academy of Sciences*, *111*(42), E4399–E4408. https://doi.org/10.1073/pnas.1400985111

Cole, M. J., Bailey, R. M., & New, M. G. (2014b). Tracking sustainable development with a national barometer for South Africa using a downscaled “safe and just space” framework. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(42), E4399–E4408. https://doi.org/10.1073/pnas.1400985111

Cox, P. M., Pearson, D., Booth, B. B., Friedlingstein, P., Huntingford, C., Jones, C. D., & Luke, C. M. (2013). Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability. *Nature*, *494*(7437), 341–344. https://doi.org/10.1038/nature11882

Dalin, C., Wada, Y., Kastner, T., & Puma, M. J. (2017). Groundwater depletion embedded in international food trade. *Nature*, *543*(7647), 700–704. https://doi.org/10.1038/nature21403

D’Almeida, C., Vörösmarty, C. J., Hurtt, G. C., Marengo, J. A., Dingman, S. L., & Keim, B. D. (2007). The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. *International Journal of Climatology*, *27*(5), 633–647. https://doi.org/10.1002/joc.1475

Dao, Q.-H., Peduzzi, P., Chatenoux, B., De Bono, A., Schwarzer, S., & Friot, D. (2015). *Environmental limits and Swiss footprints based on Planetary Boundaries*. Geneva: Swiss Federal Office for the Environment (FOEN). Retrieved from https://archive-ouverte.unige.ch/unige:74873

Deane, D. C., Nicol, J. M., Gehrig, S. L., Harding, C., Aldridge, K. T., Goodman, A. M., & Brookes, J. D. (2017). Hydrological-niche models predict water plant functional group distributions in diverse wetland types. *Ecological Applications*, *27*(4), 1351–1364. https://doi.org/10.1002/eap.1529

Dearing, J. A., Wang, R., Zhang, K., Dyke, J. G., Haberl, H., Hossain, M. S., … Poppy, G. M. (2014). Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change*, *28*, 227–238. https://doi.org/10.1016/j.gloenvcha.2014.06.012

Destouni, G., Jaramillo, F., & Prieto, C. (2012). Hydroclimatic shifts driven by human water use for food and energy production. *Nature Climate Change*, *2*(11), 1–5. https://doi.org/10.1038/nclimate1719

Dickerson-Lange, S. E., & Mitchell, R. (2014). Modeling the effects of climate change projections on streamflow in the Nooksack River basin, Northwest Washington. *Hydrological Processes*, *28*(20), 5236–5250. https://doi.org/10.1002/hyp.10012

Dingman, S. L. (2002). *Physical hydrology*. Upper Saddle River : Prentice-Hall ;

Eamus, D., Zolfaghar, S., Villalobos-Vega, R., Cleverly, J., & Huete, A. (2015). Groundwater-dependent ecosystems: recent insights from satellite and field-based studies. *Hydrology and Earth System Sciences*, *19*(10), 4229–4256. https://doi.org/10.5194/hess-19-4229-2015

Earle, A., Cascao, A. E., Hansson, S., Jägerskog, A., Swain, A., Öjendal, J., … Öjendal, J. (2015). *Transboundary Water Management and the Climate Change Debate*. Routledge. https://doi.org/10.4324/9780203098929

Ellis, S., Mellor, T., & Mellor, T. (2002). *Soils and Environment*. Routledge. https://doi.org/10.4324/9780203415245

van der Ent, R. J., Savenije, H. G. G., Schaefli, B., & Steele-Dunne, S. C. (2010). Origin and fate of atmospheric moisture over continents. *Water Resources Research*, *46*(9), 1–12. https://doi.org/10.1029/2010WR009127

Falkenmark, M. (1989). The massive water scarcity now threatening Africa: why isn’t it being addressed? *Ambio*, 112–118.

Falkenmark, M., & Rockstrom, J. (2006). The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management. *Journal of Water Resources Planning and Management*, *132*(3), 129–132. Retrieved from http://link.aip.org/link/?QWR/132/129/1 http://dx.doi.org/10.1061/(ASCE)0733-9496(2006)132:3(129)

Falkenmark, M., Wang-Erlandsson, L., & Rockström, J. (2019). Understanding of water resilience in the Anthropocene. *Journal of Hydrology X*, *2*, 100009.

Fan, Y., Li, H., & Miguez-Macho, G. (2013). Global patterns of groundwater table depth. *Science*, *339*(6122), 940–943. https://doi.org/10.1126/science.1229881

Fang, Y., Leung, L. R., Duan, Z., Wigmosta, M. S., Maxwell, R. M., Chambers, J. Q., & Tomasella, J. (2017). Influence of landscape heterogeneity on water available to tropical forests in an Amazonian catchment and implications for modeling drought response. *Journal of Geophysical Research: Atmospheres*, *122*(16), 2017JD027066. https://doi.org/10.1002/2017JD027066

Feldmann, J., & Levermann, A. (2015). Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin. *Proceedings of the National Academy of Sciences*, *112*(46), 14191–14196. https://doi.org/10.1073/pnas.1512482112

Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K., & Chappell, J. (1998). Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth and Planetary Science Letters*, *163*(1), 327–342. https://doi.org/10.1016/S0012-821X(98)00198-8

Galaz, V., Biermann, F., Folke, C., Nilsson, M., & Olsson, P. (2012). Global environmental governance and planetary boundaries: An introduction. *Ecological Economics*, *81*, 1–3. https://doi.org/10.1016/j.ecolecon.2012.02.023

Geist, H. J., & Lambin, E. F. (2004). Dynamic Causal Patterns of Desertification. *BioScience*, *54*(9), 817–829. https://doi.org/10.1641/0006-3568(2004)054[0817:DCPOD]2.0.CO;2

George, R. J., Nulsen, R. A., Ferdowsian, R., & Raper, G. P. (1999). Interactions between trees and groundwaters in recharge and discharge areas - A survey of Western Australian sites. *Agricultural Water Management*, *39*(2–3), 91–113. https://doi.org/10.1016/S0378-3774(98)00073-0

Gerten, D. (2013). A vital link: water and vegetation in the Anthropocene. *Hydrology and Earth System Sciences*, *17*(10), 3841–3852. https://doi.org/10.5194/hess-17-3841-2013

Gerten, D., Rockström, J., Heinke, J., Steffen, W., Richardson, K., & Cornell, S. (2015a). Response to Comment on “Planetary boundaries: Guiding human development on a changing planet.” *Science*, *348*(6240), 1217–1217. https://doi.org/10.1126/science.aab0031

Gerten, D., Rockström, J., Heinke, J., Steffen, W., Richardson, K., & Cornell, S. (2015b). Response to Comment on “Planetary boundaries: Guiding human development on a changing planet.” *Science*, *348*(6240), 1217–1217. https://doi.org/10.1126/science.aab0031

Gido, K. B., Dodds, W. K., & Eberle, M. E. (2010). Retrospective analysis of fish community change during a half-century of landuse and streamflow changes. *Journal of the North American Benthological Society*, *29*(3), 970–987.

Giménez, R., Mercau, J., Nosetto, M., Páez, R., & Jobbágy, E. (2016). The ecohydrological imprint of deforestation in the semiarid Chaco: insights from the last forest remnants of a highly cultivated landscape. *Hydrological Processes*, *30*(15), 2603–2616. https://doi.org/10.1002/hyp.10901

Gleeson, T., & Manning, A. H. (2008). Regional groundwater flow in mountainous terrain: Three-dimensional simulations of topographic and hydrogeologic controls. *Water Resources Research*, *44*. Retrieved from http://dx.doi.org/10.1029/2008WR006848

Gleeson, T., & Richter, B. (2018). How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers. *River Research and Applications*, *34*(1), 83–92. https://doi.org/10.1002/rra.3185

Gleick, P. H. (2000). *The world’s water 2000-2001*. Washington: Island Press.

Gordon, L. J., Steffen, W., Jönsson, B. F., Folke, C., Falkenmark, M., & Johannessen, Å. (2005). Human modification of global water vapor flows from the land surface. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(21), 7612 –7617. https://doi.org/10.1073/pnas.0500208102

Guillod, B. P., Orlowsky, B., Miralles, D. G., Teuling, A. J., & Seneviratne, S. I. (2015). Reconciling spatial and temporal soil moisture effects on afternoon rainfall. *Nature Communications*, *6*, 6443. https://doi.org/10.1038/ncomms7443

Häyhä, T., Lucas, P. L., van Vuuren, D. P., Cornell, S. E., & Hoff, H. (2016a). From Planetary Boundaries to national fair shares of the global safe operating space — How can the scales be bridged? *Global Environmental Change*, *40*, 60–72. https://doi.org/10.1016/j.gloenvcha.2016.06.008

Häyhä, T., Lucas, P. L., van Vuuren, D. P., Cornell, S. E., & Hoff, H. (2016b). From Planetary Boundaries to national fair shares of the global safe operating space — How can the scales be bridged? *Global Environmental Change*, *40*, 60–72. https://doi.org/10.1016/j.gloenvcha.2016.06.008

Häyhä, T., Cornell, S. E., Hoff, H., Lucas, P., & van Vuuren, D. (2018a). *Operationalizing the concept of a safe operating space at the EU level – first steps and explorations* (Stockholm Resilience Centre Technical Report, prepared in collaboration with Stockholm Environment Institute (SEI) and PBL Netherlands Environmental Assessment Agency). Stockholm University, Sweden: Stockholm Resilience Centre.

Häyhä, T., Cornell, S. E., Hoff, H., Lucas, P., & van Vuuren, D. (2018b). *Operationalizing the concept of a safe operating space at the EU level – first steps and explorations* (Stockholm Resilience Centre Technical Report, prepared in collaboration with Stockholm Environment Institute (SEI) and PBL Netherlands Environmental Assessment Agency). Stockholm University, Sweden: Stockholm Resilience Centre.

Heistermann, M. (2017). HESS Opinions: A planetary boundary on freshwater use is misleading. *Hydrology and Earth System Sciences*, *21*(7), 3455–3461. https://doi.org/10.5194/hess-21-3455-2017

Henshaw, P. C., Charlson, R. J., & Burges, S. J. (2000). 6 - Water and the Hydrosphere. In M. C. Jacobson, R. J. Charlson, H. Rodhe, & G. H. Orians (Eds.), *International Geophysics* (Vol. 72, pp. 109–131). Academic Press. https://doi.org/10.1016/S0074-6142(00)80112-6

Henszey, R. J., Pfeiffer, K., & Keough, J. R. (2004). Linking surface-and ground-water levels to riparian grassland species along the Platte River in Central Nebraska, USA. *Wetlands*, *24*(3), 665–687.

Hoekstra, A. Y. (2006). The global dimension of water governance: Nine reasons for global arrangements in order to cope with local water problems. Retrieved from https://research.utwente.nl/en/publications/the-global-dimension-of-water-governance-nine-reasons-for-global-

Hoekstra, A. Y., & Mekonnen, M. M. (2012). The water footprint of humanity. *Proceedings of the National Academy of Sciences*. https://doi.org/10.1073/pnas.1109936109

Houghton, R. A., Skole, D. L., Nobre, C. A., Hackler, J. L., Lawrence, K. T., & Chomentowski, W. H. (2000). Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon. *Nature*, *403*(6767), 301.

Houspanossian, J., Kuppel, S., Nosetto, M., Bella, C. D., Oricchio, P., Barrucand, M., … Jobbágy, E. (2016). Long-lasting floods buffer the thermal regime of the Pampas. *Theoretical and Applied Climatology*, 1–10. https://doi.org/10.1007/s00704-016-1959-7

Huang, K., Yi, C., Wu, D., Zhou, T., Zhao, X., Blanford, W. J., … Li, Z. (2015). Tipping point of a conifer forest ecosystem under severe drought. *Environmental Research Letters*, *10*(2), 024011. https://doi.org/10.1088/1748-9326/10/2/024011

Humphrey, V., Zscheischler, J., Ciais, P., Gudmundsson, L., Sitch, S., & Seneviratne, S. I. (2018). Sensitivity of atmospheric CO 2 growth rate to observed changes in terrestrial water storage. *Nature*, *560*(7720), 628. https://doi.org/10.1038/s41586-018-0424-4

Huntingford, C., Zelazowski, P., Galbraith, D., Mercado, L. M., Sitch, S., Fisher, R., … Cox, P. M. (2013). Simulated resilience of tropical rainforests to CO2-induced climate change. *Nature Geoscience*, *6*(4), 268–273. https://doi.org/10.1038/ngeo1741

Immerzeel, W. W., Beek, L. P. H. van, & Bierkens, M. F. P. (2010). Climate Change Will Affect the Asian Water Towers. *Science*, *328*(5984), 1382–1385. https://doi.org/10.1126/science.1183188

IPCC. (2013). Climate Change 2013: The Physical Science Basis.

Jaramillo, F., & Destouni, G. (2015). Comment on “Planetary boundaries: Guiding human development on a changing planet.” *Science*, *348*(6240), 1217–1217. https://doi.org/10.1126/science.aaa9629

Jaramillo, F., Cory, N., Arheimer, B., Laudon, H., van der Velde, Y., Hasper, T. B., … Uddling, J. (2018). Dominant effect of increasing forest biomass on evapotranspiration: interpretations of movement in Budyko space. *Hydrol. Earth Syst. Sci.*, *22*(1), 567–580. https://doi.org/10.5194/hess-22-567-2018

Jimenez, J. A., Lugo, A. E., & Cintron, G. (1985). Tree mortality in mangrove forests. *Biotropica*, 177–185.

Kahil, T., Parkinson, S., Satoh, Y., Greve, P., Burek, P., Veldkamp, T. I., … Fischer, G. (2018). A Continental-Scale Hydroeconomic Model for Integrating Water-Energy-Land Nexus Solutions. *Water Resources Research*, *54*(10), 7511–7533.

Keys, P. W., Ent, R. J. van der, Gordon, L. J., Hoff, H., Nikoli, R., & Savenije, H. H. G. (2012). Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. *Biogeosciences*, *9*(2), 733–746. https://doi.org/10.5194/bg-9-733-2012

Konar, M., Evans, T. P., Levy, M., Scott, C. A., Troy, T. J., Vörösmarty, C. J., & Sivapalan, M. (2016). Water resources sustainability in a globalizing world: who uses the water? *Hydrological Processes*, *30*(18), 3330–3336.

Kummu, M., Guillaume, J. H. A., De Moel, H., Eisner, S., Flörke, M., Porkka, M., … Ward, P. J. (2016). The world’s road to water scarcity: Shortage and stress in the 20th century and pathways towards sustainability. *Scientific Reports*, *6*, 38495. https://doi.org/10.1038/srep38495

Kuppel, S., Houspanossian, J., Nosetto, M. D., & Jobbágy, E. G. (2015). What does it take to flood the Pampas?: Lessons from a decade of strong hydrological fluctuations. *Water Resources Research*, *51*(4), 2937–2950. https://doi.org/10.1002/2015WR016966

Lawrence, D., & Vandecar, K. (2015). Effects of tropical deforestation on climate and agriculture. *Nature Climate Change*, *5*(1), 27–36. https://doi.org/10.1038/nclimate2430

Leach, M., Raworth, K., & Rockström, J. (2013). Between social and planetary boundaries: navigating pathways in the safe and just space for humanity. In *World Social Science Report 2013: Changing Global Environments* (pp. 84–89). UNESCO. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000246073

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., & Schellnhuber, H. J. (2008). Tipping elements in the Earth’s climate system. *Proceedings of the National Academy of Sciences*, *105*(6), 1786–1793. https://doi.org/10.1073/pnas.0705414105

Lowry, C. S., & Loheide, S. P. (2010). Groundwater-dependent vegetation: Quantifying the groundwater subsidy. *Water Resources Research*, *46*(6), W06202. https://doi.org/10.1029/2009WR008874

Lucas, P., & Wilting, H. (2018). *Using planetary boundaries to support national implementation of environment-related Sustainable Development Goals* (No. PBL publication number 2748). The Hague: PBL Netherlands Environmental Assessment Agency. Retrieved from https://www.pbl.nl/en/publications/using-planetary-boundaries-to-support-national-implementation-of-environment-related-sustainable-development-goals

MacDonald, G. K., Brauman, K. A., Sun, S., Carlson, K. M., Cassidy, E. S., Gerber, J. S., & West, P. C. (2015). Rethinking agricultural trade relationships in an era of globalization. *BioScience*, *65*(3), 275–289.

Malhi, Y., Roberts, J. T., Betts, R. A., Killeen, T. J., Li, W., & Nobre, C. A. (2008). Climate change, deforestation, and the fate of the Amazon. *Science*, *319*(5860), 169–172.

Marchesini, V. A., Giménez, R., Nosetto, M. D., & Jobbágy, E. G. (2017). Ecohydrological transformation in the Dry Chaco and the risk of dryland salinity: Following Australia’s footsteps? *Ecohydrology*, *10*(4). https://doi.org/10.1002/eco.1822

McGuire, K. J., & McDonnell, J. J. (2006). A review and evaluation of catchment transit time modeling. *Journal of Hydrology*, *330*(3–4), 543–563. Retrieved from http://www.sciencedirect.com/science/article/B6V6C-4K5STFN-3/2/2463e435503c1efbdb32360e63f77127

Miguez-Macho, G., & Fan, Y. (2012). The role of groundwater in the Amazon water cycle: 1. Influence on seasonal streamflow, flooding and wetlands. *Journal of Geophysical Research: Atmospheres*, *117*(D15). https://doi.org/10.1029/2012JD017539

Miguez-Macho, G., & Fan, Y. (2012). The role of groundwater in the Amazon water cycle: 2. Influence on seasonal soil moisture and evapotranspiration. *Journal of Geophysical Research: Atmospheres*, *117*(D15), D15114. https://doi.org/10.1029/2012JD017540

Mills, L. S., Soulé, M. E., & Doak, D. F. (1993). The keystone-species concept in ecology and conservation. *BioScience*, *43*(4), 219–224.

Mitchell, J. F. B. (1989). The “Greenhouse” effect and climate change. *Reviews of Geophysics*, *27*(1), 115–139. https://doi.org/10.1029/RG027i001p00115

Montanari, A., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L., … Belyaev, V. (2013). “Panta Rhei—Everything Flows”: Change in hydrology and society—The IAHS Scientific Decade 2013–2022. *Hydrological Sciences Journal*, *58*(6), 1256–1275. https://doi.org/10.1080/02626667.2013.809088

Motew, M., Chen, X., Booth, E. G., Carpenter, S. R., Pinkas, P., Zipper, S. C., … Kucharik, C. J. (2017). The Influence of Legacy P on Lake Water Quality in a Midwestern Agricultural Watershed. *Ecosystems*, *20*(8), 1468–1482. https://doi.org/10.1007/s10021-017-0125-0

National Marine Fisheries Service. (2016). *Coastal Multispecies Recovery Plan*. Santa Rosa, CA: National Marine Fisheries Service, West Coast Region.

National Research Council. (1991). *Opportunities in the Hydrologic Sciences*. Washington, DC: The National Academies Press. Retrieved from https://doi.org/10.17226/1543

Nobre, A. D. (2014). The Future Climate of Amazonia, Scientific Assessment Report. *Sponsored by CCST-INPE, INPA and ARA, São José Dos Campos Brazil*.

Nobre, C. A., & Borma, L. D. S. (2009). ‘Tipping points’ for the Amazon forest. *Current Opinion in Environmental Sustainability*, *1*(1), 28–36. https://doi.org/10.1016/j.cosust.2009.07.003

Nogherotto, R., Coppola, E., Giorgi, F., & Mariotti, L. (2013). Impact of Congo Basin deforestation on the African monsoon. *Atmospheric Science Letters*, *14*(1), 45–51. https://doi.org/10.1002/asl2.416

Notz, D. (2009). The future of ice sheets and sea ice: Between reversible retreat and unstoppable loss. *Proceedings of the National Academy of Sciences*, pnas.0902356106. https://doi.org/10.1073/pnas.0902356106

Nummelin, A., Ilicak, M., Li, C., & Smedsrud, L. H. (2016). Consequences of future increased Arctic runoff on Arctic Ocean stratification, circulation, and sea ice cover. *Journal of Geophysical Research: Oceans*, *121*(1), 617–637.

Oki, T., Yano, S., & Hanasaki, N. (2017). Economic aspects of virtual water trade. *Environmental Research Letters*, *12*(4), 044002. https://doi.org/10.1088/1748-9326/aa625f

Oki, T., & Kanae, S. (2006). Global Hydrological Cycles and World Water Resources. *Science*, *313*(5790), 1068–1072. https://doi.org/10.1126/science.1128845

Osland, M. J., Enwright, N. M., Day, R. H., Gabler, C. A., Stagg, C. L., & Grace, J. B. (2016). Beyond just sea-level rise: considering macroclimatic drivers within coastal wetland vulnerability assessments to climate change. *Global Change Biology*, *22*(1), 1–11. https://doi.org/10.1111/gcb.13084

Pahl-Wostl, C., Gupta, J., & Petry, D. (2008). Governance and the global water system: a theoretical exploration. *Global Governance: A Review of Multilateralism and International Organizations*, *14*(4), 419–435.

Pareto, V. (1896). *Course of political economy*. Lausanne.

Perkin, J. S., Gido, K. B., Falke, J. A., Fausch, K. D., Crockett, H., Johnson, E. R., & Sanderson, J. (2017). Groundwater declines are linked to changes in Great Plains stream fish assemblages. *Proceedings of the National Academy of Sciences*, 201618936. Retrieved from http://www.pnas.org/content/early/2017/06/20/1618936114.short

Pires, G. F., & Costa, M. H. (2013). Deforestation causes different subregional effects on the Amazon bioclimatic equilibrium. *Geophysical Research Letters*, *40*(14), 3618–3623. https://doi.org/10.1002/grl.50570

Poff, N. L., & Matthews, J. H. (2013). Environmental flows in the Anthropocence: past progress and future prospects. *Current Opinion in Environmental Sustainability*, *5*(6), 667–675.

Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., … Warner, A. (2009). The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology*, *55*(1), 147–170. Retrieved from http://dx.doi.org/10.1111/j.1365-2427.2009.02204.x

Pool, T. K., Olden, J. D., Whittier, J. B., & Paukert, C. P. (2010). Environmental drivers of fish functional diversity and composition in the Lower Colorado River Basin. *Canadian Journal of Fisheries and Aquatic Sciences*, *67*(11), 1791–1807. https://doi.org/10.1139/F10-095

Porkka, M., Kummu, M., Siebert, S., & Flörke, M. (2012). The Role of Virtual Water Flows in Physical Water Scarcity: The Case of Central Asia. *International Journal of Water Resources Development*, *28*(3), 453–474. https://doi.org/10.1080/07900627.2012.684310

Postel, S. L., Daily, G. C., & Ehrlich, P. R. (1996). Human appropriation of renewable fresh water. *Science*, *271*(5250), 785–788. https://doi.org/10.1126/science.271.5250.785

Qiuhong Tang, & Taikan Oki (Eds.). (2016). Terrestrial Water Cycle and Climate Change: Natural and Human-Induced Impacts,. In *Geophysical Monograph 221, First Edition.* (pp. 3–16). American Geophysical Union.

Raworth, K. (2017). *Doughnut economics: seven ways to think like a 21st-century economist*. Chelsea Green Publishing.

Reager, J. T., Gardner, A. S., Famiglietti, J. S., Wiese, D. N., Eicker, A., & Lo, M.-H. (2016). A decade of sea level rise slowed by climate-driven hydrology. *Science*, *351*(6274), 699–703. https://doi.org/10.1126/science.aad8386

Richey, A. S., Thomas, B. F., Lo, M.-H., Reager, J. T., Famiglietti, J. S., Voss, K., … Rodell, M. (2015). Quantifying renewable groundwater stress with GRACE. *Water Resources Research*, *51*(7), 5217–5238. https://doi.org/10.1002/2015WR017349

Richter, B. D., Mathews, R., Harrison, D. L., & Wigington, R. (2003). Ecologically sustainably water management: managing river flows for ecological integrity. *Ecological Applications*, *13*(1), 206–224. https://doi.org/10.1890/1051-0761(2003)013[0206:ESWMMR]2.0.CO;2

Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A., & Thomas, R. (2004). Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophysical Research Letters*, *31*(18). https://doi.org/10.1029/2004GL020697

Rocha, J. C., Peterson, G., Bodin, Ö., & Levin, S. (2018). Cascading regime shifts within and across scales. *Science*, *362*(6421), 1379–1383.

Rockström, J. (2017). Interactive comment on "HESS Opinions: A Planetary Boundary on Freshwater Use is Misleading" by Maik Heistermann.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. I., Lambin, E., … Foley, J. (2009a). Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society*, *14*(2). https://doi.org/10.5751/ES-03180-140232

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., … Foley, J. A. (2009b). A safe operating space for humanity. *Nature*, *461*(7263), 472–475. https://doi.org/10.1038/461472a

Rockström, J., Falkenmark, M., Folke, C., Lannerstad, M., Barron, J., Enfors, E., … Pahl-Wostl, C. (2014). *Water resilience for human prosperity*. Cambridge University Press.

Rodhe, H. (1990). A Comparison of the Contribution of Various Gases to the Greenhouse Effect. *Science*, *248*(4960), 1217–1219. https://doi.org/10.1126/science.248.4960.1217

Rohde, M. M., Froend, R., & Howard, J. (2017). A Global Synthesis of Managing Groundwater Dependent Ecosystems Under Sustainable Groundwater Policy. *Groundwater*, n/a-n/a. https://doi.org/10.1111/gwat.12511

Schuur, E. a. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., … Vonk, J. E. (2015). Climate change and the permafrost carbon feedback. *Nature*, *520*(7546), 171–179. https://doi.org/10.1038/nature14338

Scott, M. L., Shafroth, P. B., & Auble, G. T. (1999). Responses of Riparian Cottonwoods to Alluvial Water Table Declines. *Environmental Management*, *23*(3), 347–358. https://doi.org/10.1007/s002679900191

Shibuo, Y., Jarsjö, J., & Destouni, G. (2007). Hydrological responses to climate change and irrigation in the Aral Sea drainage basin. *Geophysical Research Letters*, *34*(21). https://doi.org/10.1029/2007GL031465

Sivapalan, M. (2017). Interactive comment on "HESS Opinions: a plantary boundary on freshwater use is misleading" by Maik Heistermann. *Hydrol. Earth Syst. Sci. Discuss.*

Sivapalan, M., Savenije, H. H., & Blöschl, G. (2012). Socio-hydrology: A new science of people and water. *Hydrological Processes*, *26*(8), 1270–1276.

Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, C. A., … Rodríguez-Iturbe, I. (2014). Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. *Earth's Future*, *2*(4), 225–230.

Smakhtin, V. U., Revenga, C., & Döll, P. (2004). A pilot global assessment of environmental water requirements and scarcity. *Water International*, *29*(3), 307–317.

Smith, T. J. (1992). Forest Structure. In A. I. Robertson & D. M. Alongi (Eds.), *Tropical Mangrove Ecosystems* (pp. 101–136). American Geophysical Union. Retrieved from http://onlinelibrary.wiley.com/doi/10.1029/CE041p0101/summary

Smith, V. H., & Schindler, D. W. (2009). Eutrophication science: where do we go from here? *Trends in Ecology & Evolution*, *24*(4), 201–207.

Sood, A., & Smakhtin, V. (2015). Global hydrological models: a review. *Hydrological Sciences Journal*, *60*(4), 549–565.

Soylu, M. E., Kucharik, C. J., & Loheide, S. P. (2014). Influence of groundwater on plant water use and productivity: Development of an integrated ecosystem – Variably saturated soil water flow model. *Agricultural and Forest Meteorology*, *189–190*, 198–210. https://doi.org/10.1016/j.agrformet.2014.01.019

Soylu, M. E., Istanbulluoglu, E., Lenters, J. D., & Wang, T. (2011). Quantifying the impact of groundwater depth on evapotranspiration in a semi-arid grassland region. *Hydrology and Earth System Sciences*, *15*(3), 787–806. https://doi.org/10.5194/hess-15-787-2011

Staver, A. C., Archibald, S., & Levin, S. A. (2011). The Global Extent and Determinants of Savanna and Forest as Alternative Biome States. *Science*, *334*(6053), 230–232. https://doi.org/10.1126/science.1210465

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., … Crucifix, M. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, *115*(33), 8252–8259.

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015a). The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review*, *2*(1), 81–98. https://doi.org/10.1177/2053019614564785

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., … Sörlin, S. (2015b). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223). https://doi.org/10.1126/science.1259855

Summerfield, M. A. (2005). The changing landscape of geomorphology. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *30*(6), 779–781.

Summerfield, M. A. (2014). *Global geomorphology*. Routledge.

Syvitski, J. P., Kettner, A. J., Overeem, I., Hutton, E. W., Hannon, M. T., Brakenridge, G. R., … Giosan, L. (2009). Sinking deltas due to human activities. *Nature Geoscience*, *2*(10), 681.

Syvitski, J. P. M. (2002). Sediment discharge variability in Arctic rivers: implications for a warmer future. *Polar Research*, *21*(2), 323–330. https://doi.org/10.1111/j.1751-8369.2002.tb00087.x

Tessler, Z. D., Vörösmarty, C. J., Overeem, I., & Syvitski, J. P. (2018). A model of water and sediment balance as determinants of relative sea level rise in contemporary and future deltas. *Geomorphology*, *305*, 209–220.

Tierney, J. E., Pausata, F. S. R., & De Menocal, P. B. (2017). Rainfall regimes of the Green Sahara. *Science Advances*, *3*(1). https://doi.org/10.1126/sciadv.1601503

Tietsche, S., Notz, D., Jungclaus, J. H., & Marotzke, J. (2011). Recovery mechanisms of Arctic summer sea ice. *Geophysical Research Letters*, *38*(2). https://doi.org/10.1029/2010GL045698

Tölgyessy, J. (1993). *Chemistry and biology of water, air and soil: Environmental aspects* (Vol. 53). Elsevier.

Tóth, J. (1963). A theoretical analysis of groundwater flow in small drainage basins. *Journal of Geophysical Research*, *68*(16), 4795–4812.

Tuinenburg, O. A. (2013). *Atmospheric Effects of Irrigation in Moonsoon Climate: The Indian Subcontinent* (PhD Thesis). Wageningen University.

Twilley, R. R., & Rivera-Monroy, V. H. (2005). Developing Performance Measures of Mangrove Wetlands Using Simulation Models of Hydrology, Nutrient Biogeochemistry, and Community Dynamics. *Journal of Coastal Research*, 79–93. Retrieved from http://www.jstor.org/stable/25736617

UNESCO. (1978). *World water balance and water resources of the earth* (Vol. USSR committee for the international hydrologic decade). Paris: UNESCO.

Varady, R. G., Meehan, K., & McGovern, E. (2009). Charting the emergence of 'global water initiatives' in world water governance. *Physics and Chemistry of the Earth, Parts A/B/C*, *34*(3), 150–155. https://doi.org/10.1016/j.pce.2008.06.004

Velicogna, I., Sutterley, T. C., & van den Broeke, M. R. (2014a). Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data. *Geophysical Research Letters*, *41*(22), 8130–8137. https://doi.org/10.1002/2014GL061052

Velicogna, I., Sutterley, T. C., & van den Broeke, M. R. (2014b). Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data. *Geophysical Research Letters*, *41*(22), 8130–8137. https://doi.org/10.1002/2014GL061052

Vilà-Guerau de Arellan, J., van Heerwaarden, C. C., van Stratum, B. J. H., & van den Dries, K. (2015). *Atmospheric boundary layer integrating air chemistry and land interactions | Atmospheric science and meteorology*. Cambridge University Press.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., … Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, *467*(7315), 555–561. https://doi.org/10.1038/nature09440

Vörösmarty, C. J., Hoekstra, A. Y., Bunn, S. E., Conway, D., & Gupta, J. (2015). Fresh water goes global. *Science*, *349*(6247), 478–479. https://doi.org/10.1126/science.aac6009

Wada, Y. (2016). Modeling Groundwater Depletion at Regional and Global Scales: Present State and Future Prospects. *Surveys in Geophysics*, *37*(2), 419–451. https://doi.org/10.1007/s10712-015-9347-x

Wada, Y., Gleeson, T., & Esnault, L. (2014). Wedge approach to water stress. *Nature Geosci*, *7*(9), 615–617. https://doi.org/10.1038/ngeo2241

Wada, Y., Lo, M.-H., Yeh, P. J.-F., Reager, J. T., Famiglietti, J. S., Wu, R.-J., & Tseng, Y.-H. (2016). Fate of water pumped from underground and contributions to sea-level rise. *Nature Climate Change*, *6*(8), 777–780. https://doi.org/10.1038/nclimate3001

Wagener, T., Sivapalan, M., Troch, P. A., McGlynn, B. L., Harman, C. J., Gupta, H. V., … Wilson, J. S. (2010). The future of hydrology: An evolving science for a changing world. *Water Resources Research*, *46*(5).

Wagener, T., Sivapalan, M., Troch, P., & Woods, R. (2007). Catchment Classification and Hydrologic Similarity. *Geography Compass*, *1*(4), 901–931. https://doi.org/10.1111/j.1749-8198.2007.00039.x

Wang, C., & Temmerman, S. (2013). Does biogeomorphic feedback lead to abrupt shifts between alternative landscape states ?: An empirical study on intertidal flats and marshes, *118*, 229–240. https://doi.org/10.1029/2012JF002474

Wang-Erlandsson, L., Fetzer, I., Keys, P. W., Ent, R. J. van der, Savenije, H. H. G., & Gordon, L. J. (2018). Remote land use impacts on river flows through atmospheric teleconnections. *Hydrology and Earth System Sciences*, *22*(8), 4311–4328. https://doi.org/10.5194/hess-22-4311-2018

Watson, K. A., Mayer, A. S., & Reeves, H. W. (2014). Groundwater Availability as Constrained by Hydrogeology and Environmental Flows. *Groundwater*, *52*(2), 225–238. https://doi.org/10.1111/gwat.12050

Weiskel, P. K., Vogel, R. M., Steeves, P. A., Zarriello, P. J., DeSimone, L. A., & Ries, K. G., III. (2007). Water use regimes: Characterizing direct human interaction with hydrologic systems. *Water Resour. Res.*, *43*(4), W04402. Retrieved from http://dx.doi.org/10.1029/2006WR005062

Whitford, W. G., Virginia, R. A., Huenneke, L. F., Reynolds, J. F., Schlesinger, W. H., Jarrell, W. M., & Cunningham, G. L. (2006). Biological Feedbacks in Global Desertification. *Science*, *247*(4946), 1043–1048. https://doi.org/10.1126/science.247.4946.1043

Wiens, J. A., Moss, M. R., Fahrig, L., & Milne, B. (2005). *Issues and perspectives in landscape ecology*. Cambridge University Press.

Xu, J., Grumbine, R. E., Shrestha, A., Eriksson, M., Yang, X., Wang, Y., & Wilkes, A. (2009). The Melting Himalayas: Cascading Effects of Climate Change on Water, Biodiversity, and Livelihoods. *Conservation Biology*, *23*(3), 520–530. https://doi.org/10.1111/j.1523-1739.2009.01237.x

Yeh, P. J.-F., & Famiglietti, J. S. (2009). Regional groundwater evapotranspiration in Illinois. *Journal of Hydrometeorology*, *10*(2), 464–478. https://doi.org/10.1175/2008JHM1018.1

Yu, K., D'Odorico, P., Bhattachan, A., Okin, G. S., & Evan, A. T. (2015). Dust-rainfall feedback in West African Sahel. *Geophysical Research Letters*, *42*(18), 7563–7571. https://doi.org/10.1002/2015GL065533

Zalasiewicz, J., Waters, C. N., Williams, M., Barnosky, A. D., Cearreta, A., Crutzen, P., … Oreskes, N. (2015). When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. *Quaternary International*, *383*, 196–203. https://doi.org/10.1016/j.quaint.2014.11.045

Zemp, D. C., Schleussner, C.-F., Barbosa, H. M. J., Hirota, M., Montade, V., Sampaio, G., … Rammig, A. (2017). Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nature Communications*, *8*, 14681. https://doi.org/10.1038/ncomms14681

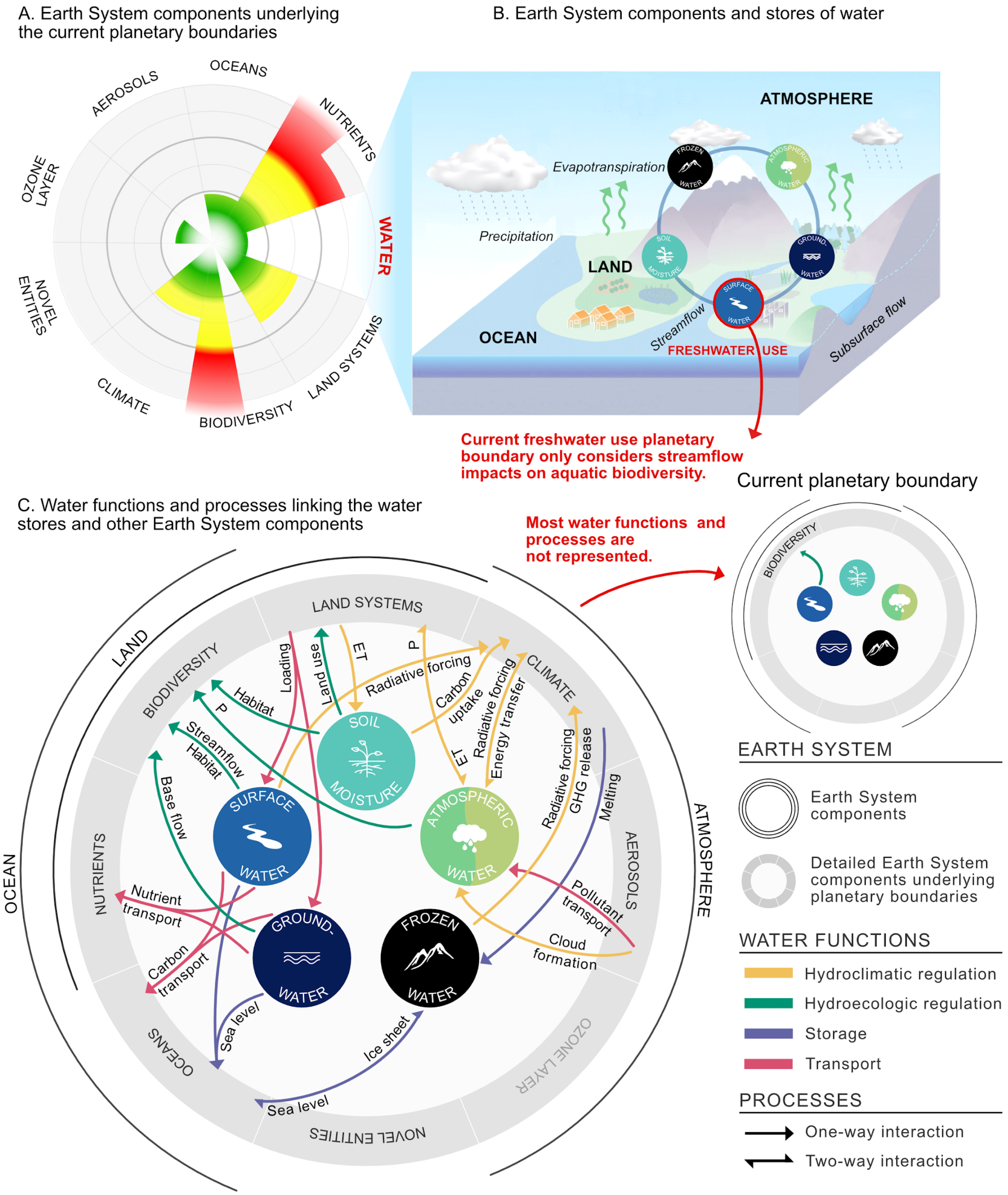
Ziegler, R., Gerten, D., & Döll, P. (2017). Safe, just and sufficient space: the planetary boundary for human water use in a more-than-human world. *Global Water Ethics. Towards a Global Ethics Charter. Routledge, London*, 109–130.

Zipper, S. C., Soylu, M. E., Kucharik, C. J., & Loheide II, S. P. (2017). Quantifying indirect groundwater-mediated effects of urbanization on agroecosystem productivity using MODFLOW-AgroIBIS (MAGI), a complete critical zone model. *Ecological Modelling*, *359*, 201–219. https://doi.org/10.1016/j.ecolmodel.2017.06.002

Zipper, S. C., Soylu, M. E., Booth, E. G., & Loheide, S. P. (2015). Untangling the effects of shallow groundwater and soil texture as drivers of subfield-scale yield variability. *Water Resources Research*, *51*(8), 6338–6358. https://doi.org/10.1002/2015WR017522

Zipper, S. C., Lamontagne-Hallé, P., McKenzie, J. M., & Rocha, A. V. (2018). Groundwater controls on post-fire permafrost thaw: Water and energy balance effects. *Journal of Geophysical Research: Earth Surface*, *123*(10), 2677–2694. https://doi.org/10.1029/2018JF004611

Figures



A. Earth System components underlying the current planetary boundaries

B. Earth System components and stores of water

C. Water functions and processes linking the water stores and other Earth System components

Current freshwater use planetary boundary only considers streamflow impacts on aquatic biodiversity.

Most water functions and processes are not represented.

Current planetary boundary

EARTH SYSTEM

Earth System components

Detailed Earth System components underlying planetary boundaries

WATER FUNCTIONS

Hydroclimatic regulation

Hydroecologic regulation

Storage

Transport

PROCESSES

One-way interaction

Two-way interaction

Figure 1. Freshwater use is one of the (a) current planetary boundaries, yet affecting only a small component of (b) the hydrosphere, which includes numerous stores of water. 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. (c) The core functions of water in the Earth System (larger diagram) and how they are represented in the current freshwater use planetary boundary (small diagram). Diagrams show 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). The arrows denote processes linking the water stores and the Earth System components, color-coded by Earth System functions of water (hydroclimate, hydroecology, storage, and transport). Note that in figures, hydroclimatic and hydroecological regulation are shorted to hydroclimate and hydroecology; P is precipitation and ET is evapotranspiration. Figures (a) and (b) are modified from Steffen et al. (2015) and Oki and Kanae (2006), respectively.

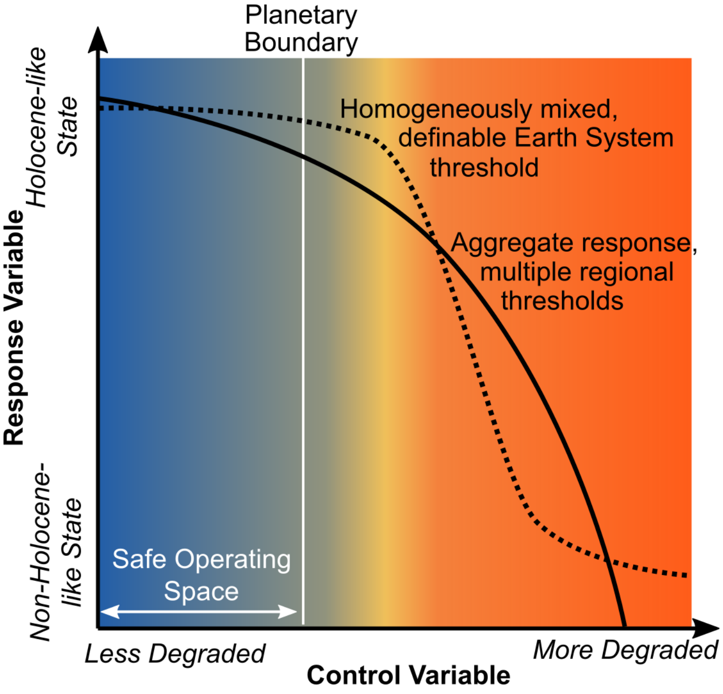
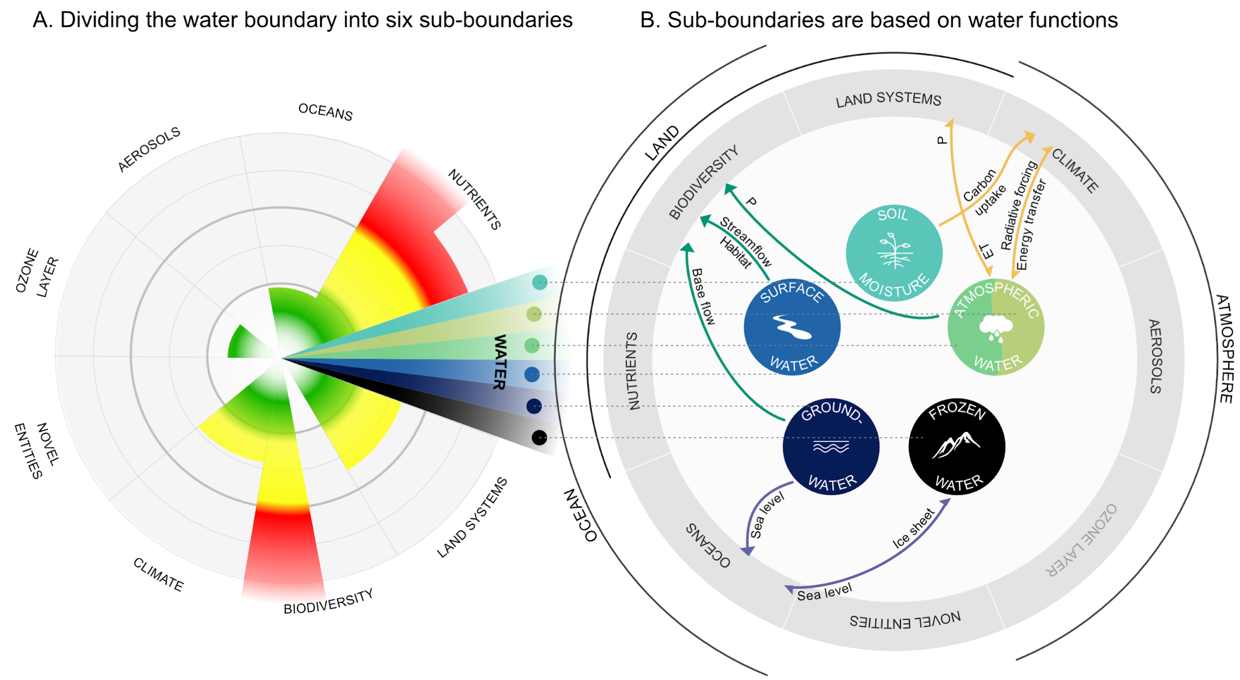


Figure 2. Graphical framework for the definition of the planetary boundaries, showing two types of relationships between a control and response variable (modified from Steffen et al., 2015).



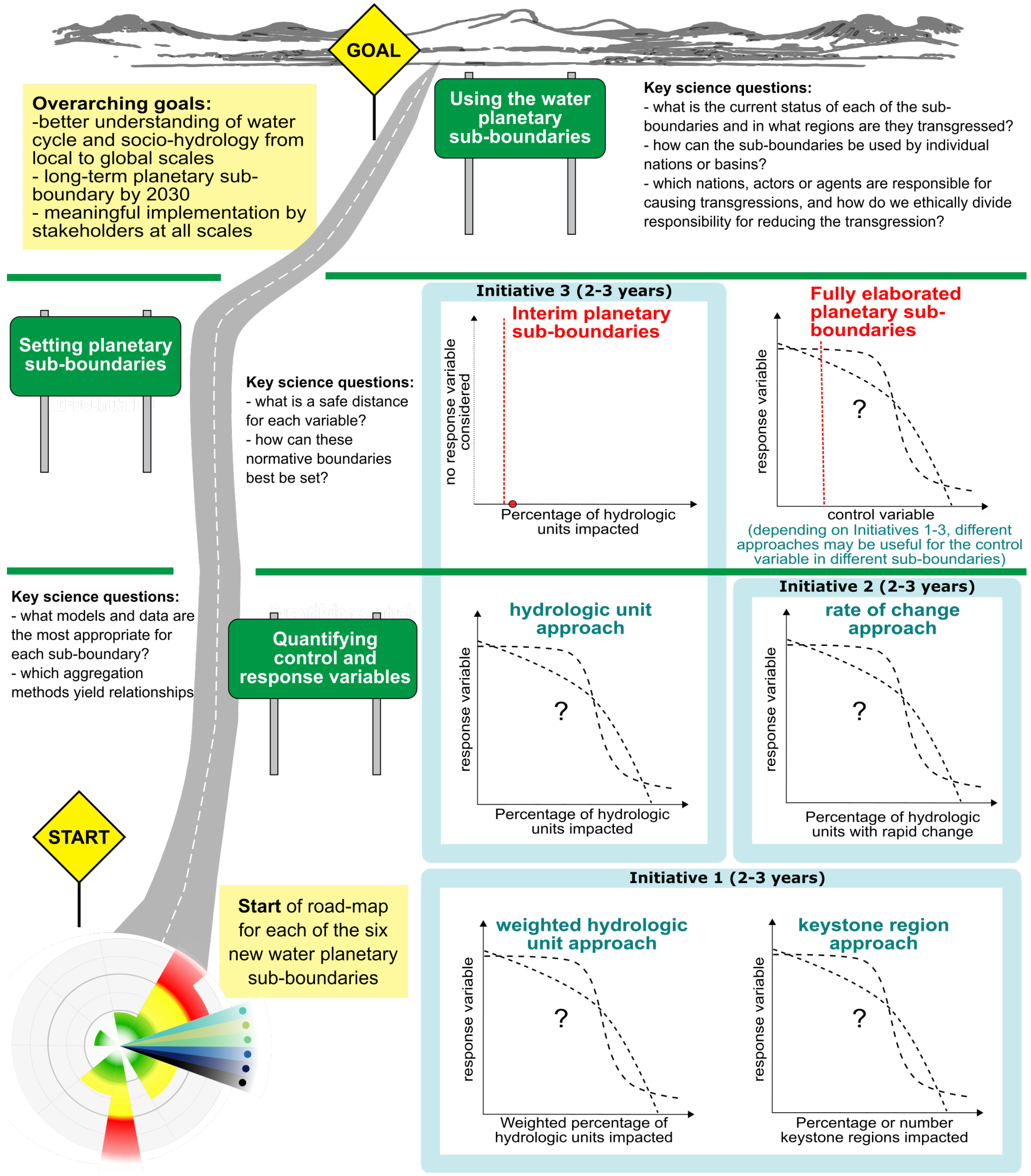
A. Dividing the water boundary into six sub-boundaries

B. Sub-boundaries are based on water functions

C. Key aspects of each of the proposed water sub-boundaries

	ATMOSPHERIC WATER (hydroclimatic regulation)	**ATMOSPHERIC WATER** (hydroecologic regulation)	**SOIL MOISTURE** (hydroclimatic regulation)	**SURFACE WATER** (hydroecologic regulation)	**GROUNDWATER** (storage)	**FROZEN WATER** (storage)
Possible scale of analysis	Precipitationsheds	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 evapo-transpiration 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 3. Revising the water planetary boundary to include six potential water planetary sub-boundaries. (a) A possible future planetary boundary overview figure with the six divided water stores. (b) Defining water planetary sub-boundaries based on the functional relationship between water stores and Earth System components; same as Figure 1c with only the functions used to define the sub-boundaries shown. (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 Earth System functions of water for each sub-boundary are identified in parentheses (such as hydroecology for surface water).



Overarching goals:
- better understanding of water cycle and socio-hydrology from local to global scales
- long-term planetary sub-boundary by 2030
- meaningful implementation by stakeholders at all scales

Key science questions:
- what is the current status of each of the sub-boundaries and in what regions are they transgressed?
- how can the sub-boundaries be used by individual nations or basins?
- which nations, actors or agents are responsible for causing transgressions, and how do we ethically divide responsibility for reducing the transgression?

Key science questions:
- what is a safe distance for each variable?
- how can these normative boundaries best be set?

(depending on Initiatives 1-3, different approaches may be useful for the control variable in different sub-boundaries)

Key science questions:
- what models and data are the most appropriate for each sub-boundary?
- which aggregation methods yield relationships

Start of road-map for each of the six new water planetary sub-boundaries

Figure 4. A roadmap for developing the new spatially-explicit water planetary sub-boundaries as described in Section 3 of the text. The horizontal axes on all graphs are the proposed control variables.

Tables

Table 1. Definition of key words.

Key word	Definition
consumptive blue water use	Blue water refers to freshwater in lakes, rivers, reservoirs and renewable groundwater stores. In contrast, green water is the precipitation that adds to soil moisture and that does not run off, eventually evaporating or transpiring. Consumptive use of freshwater refers to the water amount used and not returned to runoff.
control variable	a quantifiable biophysical indicator representing some aspect of the Earth System over which humans can exert an influence
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
Earth System component	Major Earth System components refer to land, atmosphere, biosphere and climate. Detailed Earth System components refer to components related to Planetary Boundaries such as nutrients, biodiversity, land systems etc.
water stores	hydrologic stores such as atmospheric water, surface water, soil moisture, groundwater and frozen water
Earth System functions of water	critical functions or roles of freshwater in the Earth System including hydroclimatic regulation, hydroecological regulation, storage and transport. The Earth System functions of water differ from Falkenmark et al. (XX) who describe 'water functions' that distinguish green and blue water functions for social-ecological resilience, whereas we focus on the functions of water explicitly in the Earth System, independent of green or blue origin. The Earth System functions of water also differ from 'watershed functions' (Black 1997; Wagener 2007) which focused watershed-scale hydrologic functions.
tipping point	critical threshold where a system shifts to an alternative state abruptly
keystone region	a region where a water store (e.g. atmospheric water) produces a disproportionately important impact and could be essential to maintaining an Earth System component (e.g. climate)

Table 2. Evaluating the current planetary boundaries for water use and different approaches to subdividing the water planetary boundaries. Each criterion is qualitatively evaluated as *met* (+), *not met* (-) or *ambiguous or uncertain* (+/-). Criteria are summed for comparison to tables although any single one is not considered more or less important. Steffen et al. (2015) is not included since they effectively re-stated the top-down (Rockström et al., 2009a,b) and bottom-up (Gerten et al., 2013) calculations.

Criteria	**Rockström et al 2009a**	**Gerten et al 2013**	**Subdividing based on water functions**	**Subdividing based on water stores**
1) Planetary boundary variables	- Maximum amount of consumptive blue water use considered proxy control variable (~4000 km^3/year); response variable and relationship both unclear	- Considered regional impacts on aquatic ecosystems related to rivers' environmental flow requirements; response variable and relationship remain unclear	+/- uncertain	+/- Possible. To be developed, see Sect 3.2, 3.3 and Fig. 4.
2) Regional impacts and upscaling mechanisms	+/- Evidence of regional water scarcity and environmental flow transgressions but top-down approach largely neglects spatiotemporal heterogeneity; unclear scaling mechanisms, planetary boundary is thought to represent the aggregate of human interference in catchment water balances	+/- Focused on environmental flow transgressions and their impacts on aquatic ecosystems in a spatially explicit manner but scaling mechanisms remain unclear; very partial perspective excluding other water effects	- Evidence and mechanisms challenging since function not directly physically based	+ Evidence and mechanisms could be derived from physically based models and data, see Sect. 3.2 3.3, and Fig 4.
3) Impacts on Earth System stability	- Water consumption and associated environmental flow transgressions could potentially impact Earth System stability through the biosphere integrity planetary boundary, however, global aggregate metric does not capture heterogeneity or underlying mechanisms	+/- See column to the left; spatiotemporal heterogeneity is better taken into account, but unlikely that all basins/regions carry equal weight for biosphere integrity, as the method suggests	- Assessing impacts challenging since function not directly physically based	+ Impacts could be assessed from physically based models and data, see Sect. 3.2.
4) Measurable	+/- Status of boundary approximately measurable with models and country statistics - however significant debate on uncertainties, on what to include, and how to calculate (Jaramillo & Destouni 2015)	+/- See column to the left	- Unclear what would be directly measured	+ Potentially measurable, see Sect. 3.2 and 3.3.
5) Understand-able and operationa-lizable	+/- Understandable but also leads to significant confusion since water use only considered proxy control variable, can be misinterpreted as regional transgressions are not explicitly captured and unclear how to operationalize	+/- See column to the left)	+/- uncertain	+/- Potentially possible. To be developed, see discussion in Sect. 3.5.
6) Represents regional and global impacts	- Does not specifically represent regional impacts and aggregates global impacts based on fluxes	+/- Spatially represents regional transgressions of environmental flow needs and aggregates flows globally	+/- uncertain	+/- Potentially possible. To be developed, see Fig. 4.
7) Uniqueness	+/- Interacts with planetary boundaries of biosphere integrity, land use change and climate change, and to a lesser degree ocean acidification and biogeochemical flows. Is unique in representing the water system	+/- See left, although more directly interacts with biosphere integrity planetary boundary through environmental flow requirements	+/- See left.	+/- For interactions (and potential overlaps with other planetary boundaries), see Fig 1.
Total criteria met	**0/7**	**0/7**	**0/7**	**3/7**