One Earth
Perspective

The Water Planetary Boundary: Interrogation and Revision

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The planetary boundaries framework proposes quantified guardrails to human modification of global environmental processes that regulate the stability of the planet and has been considered in sustainability science, governance, and corporate management. However, the planetary boundary for human freshwater use has been critiqued as a singular measure that 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, frozen water, groundwater, soil moisture, and surface water. This paper provides an ambitious scientific road map to define a new water planetary boundary consisting of sub-boundaries that account for a variety of changes to the water cycle.

The Challenges and Possibilities of a Water Planetary Boundary

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 are a global environmental sustainability framework for identifying critical transitions or tipping points in the complex Earth System, based on control and response variables (Figure 2; see Box 1 for an overview of the planetary boundary framework and definitions of control and response variables). 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."[1] Blue water refers to freshwater in lakes, rivers, reservoirs, and groundwater stores while green water is the precipitation that adds to soil moisture and does not run off, eventually evaporating or transpiring. Consumptive use of freshwater refers to the water amount used and not returned to runoff. Rockström et al.[1] 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

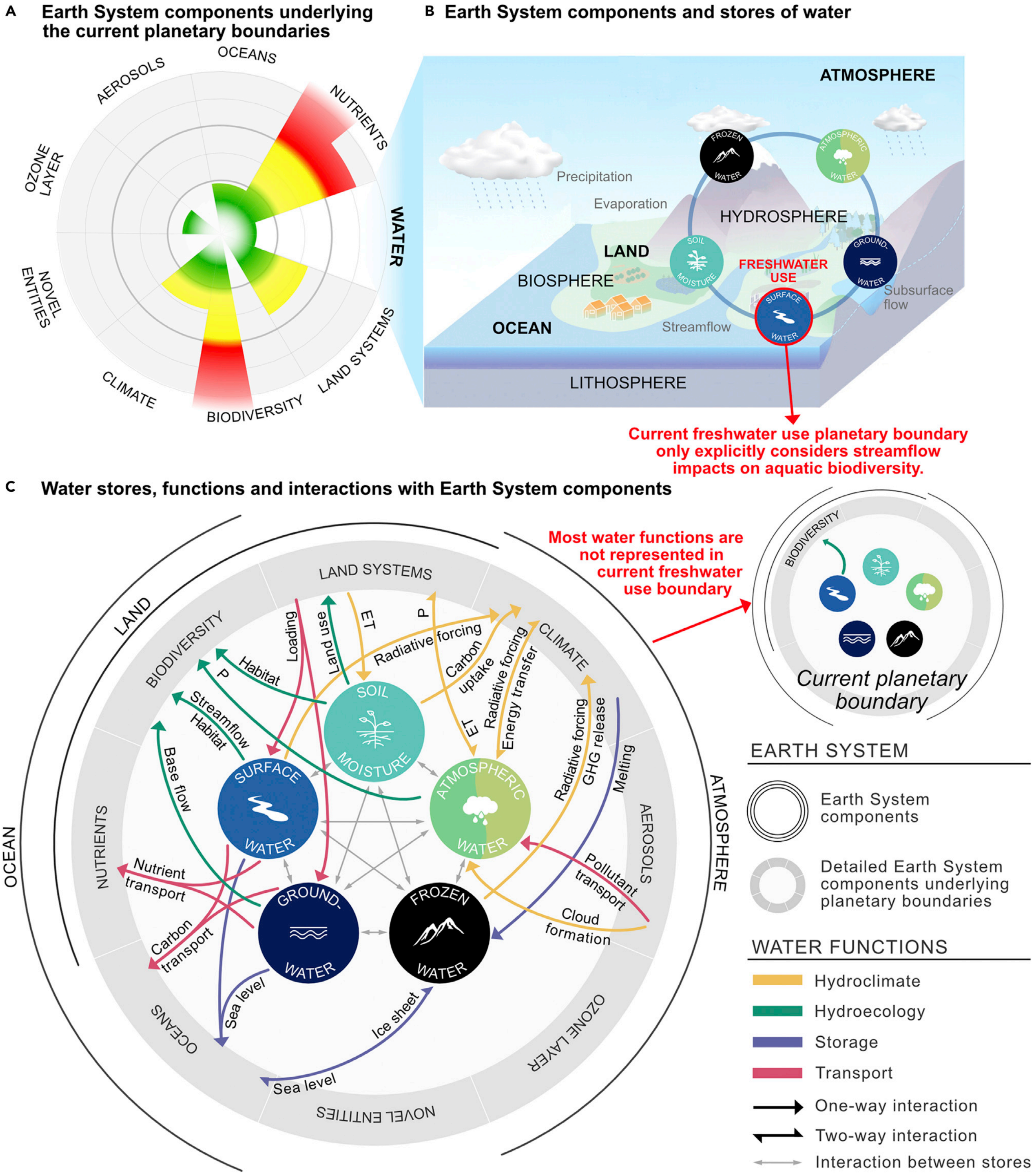


Figure 1. The Water Planetary Boundary and Related Earth System Components and Functions

(A and B) Freshwater use is one of (A) the 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 gray 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 hydroclimatic and hydroecological regulation are shortened to hydroclimate and hydroecology; P is precipitation and ET is evapotranspiration. The green zone in (A) is the safe operating space, yellow represents the zone of uncertainty (increasing risk), and red is a high-risk zone. Modified from Steffen et al. (A),[3] Oki and Kanae (B),[4] and Gleeson et al. (C).[5]

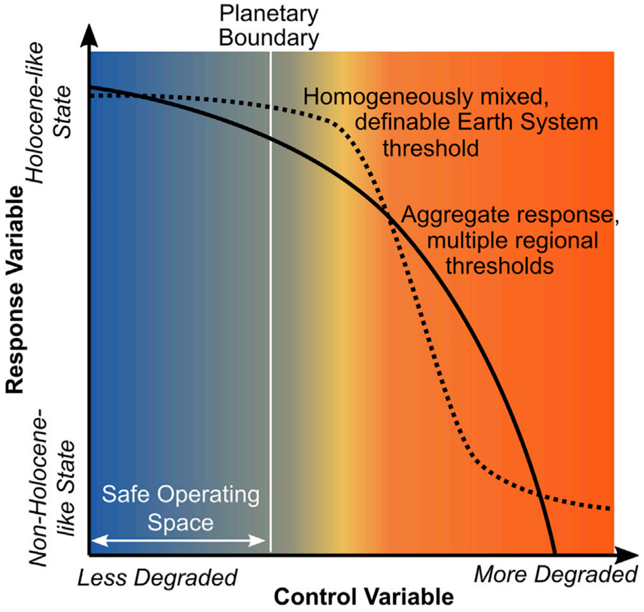


Figure 2. Planetary Boundary Framework Showing Two of the Many Potential Types of Relationships between a Control and Response Variable

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.[2] proposed quantifying the boundary by assessing the amount of streamflow needed to maintain environmental flow requirements in all river basins on Earth, which suggested a freshwater use planetary boundary of 2,800 km^3/year (the average of an uncertainty range of 1,100–4,500 km^3/year).

While the planetary boundary framework garnered interest from international bodies such as the United Nations[9] as well as from the corporate sustainability sector,[10] 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 boundary,[11–14] although 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 oversimplifications of the current freshwater use planetary boundary, which raises the fundamental question of the relevance or value of a water planetary boundary for environmental governance and for water management specifically.

The Relevance of a Water Planetary Boundary for Water Management and Environmental Governance, and Our Understanding of Socio-hydrological Systems across Scales

Water has been identified as one of the planetary boundaries highlighting the critical role played by water 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 played by water in the functioning and stability of the Earth System and the habitability of Earth for humankind.[15] Defining a water planetary boundary could be part of the large and growing field of water-resource management, which addresses the constantly evolving nexus of hydrology and society.[16–21] Adding a simplified aspirational and global metric to the toolbox does not suggest that spatial heterogeneity of water issues should be ignored or local-scale data or metrics be superseded. The water planetary boundary is useful because it serves a distinct and complementary purpose to other water-resource management methods, tools, and frameworks in four ways:

- Considering that water flows beyond traditional basin boundaries. Research on virtual water flows,[22–24] moisture transfer,[25,26] and regional groundwater flow[27–30] 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.[31]
- 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.[32]
- Providing an assessment of the "safe operating space" for humanity (Box 1). Various water-management indicators measure impact and status such as water stress,[33–35] water depletion,[36] water scarcity,[36,37] water footprints,[38] water wedges,[39,40] water-use regimes,[41] human appropriation of evapotranspiration,[42] peak water,[43] renewable water resources,[4] water-related UN Sustainable Development Goals,[44] and hydroclimatic separation.[45] These could be complemented by information about the water-related "safe operating space" for humanity.
- Recognizing that everyone is a stakeholder in local-to-regional scale functioning of the water cycle. Eventually, disaggregating the water planetary boundary to a specific basin or jurisdiction could highlight water-management priorities for practitioners, policy makers, or stakeholders that are different than those raised by traditional local-to-regional scale water-resource management indicators.[46] The continental-to-global perspective could, for example, highlight the importance of the water balance of the Amazon rainforest for climate change,[47,48] monsoon system, and agricultural production outside the region through teleconnections and indirect impacts.[49] This could lead to the recognition of the global community's role as a stakeholder in the Amazon rainforest water cycle beyond the regional and national scale.

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. By holistically and transparently evaluating the value, concerns, and possibilities of water planetary boundary, we aim to move the debate forward in response to

Box 1. Introduction to Planetary Boundaries and Safe Operating Space

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 development by keeping Earth in a manageable Holocene-like interglacial state (Figure 2). The planetary boundary framework is based on (1) identifying relevant biogeochemical processes that regulate the stability of the Earth System and (2) determining the limit of human perturbation of these critical processes. Crossing any of the planetary boundaries could destabilize essential Earth System processes.[1,3,6]

Nine planetary boundary processes and systems have been identified. For each boundary process/system, a critical value of a control variable is defined, whereby 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 greenhouse gases 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 types, rates, locations, and sequencing of processes, some of which have critical transitions that occur at local or regional scales. These boundaries therefore represent regulatory processes that provide the underlying resilience of the Earth System.[1] If sufficiently widespread, however, human-caused perturbations to these "bottom-up" processes will have significant aggregate consequences at the global scale, with systemic or cascading interactions with other boundaries.[7]

Over geological time, the state of the Earth System is punctuated by well-defined shifts as well as slower, gradual co-evolution of the climate system and the biosphere. Steffen et al.[3] 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 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 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.

The planetary boundary positions are not equivalent to any specific threshold values in the control variables given the natural variability of Earth System dynamics, the limitations of large-scale environmental monitoring and modeling, and fundamental scientific uncertainty. 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 first focusing on defining the scientific range of uncertainty for each boundary definition. Here there are no normative judgments, only an attempt to carry out the best possible scientific assessment and disclose clearly the range of uncertainty. A normative step then follows whereby a precautionary principle is adopted (based on the complexity of the functioning of the Earth System and, in particular, interactions and feedbacks among Earth System processes) by placing the planetary boundary position, and thus the safe operating space for humanity, at the lower end of the uncertainty range for each control variable. When transgressing this boundary, humanity enters a "danger zone," constituted by the uncertainty range. 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 destabilize 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 judgments of how societies choose to deal with risks and uncertainties of global environmental change.[1,6,7] 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.[8]

recent discussions.[50–54] First, we review how the planetary boundaries are defined and identified (Box 1), which forms a basis for a new set of criteria for evaluating the current freshwater use planetary boundary, discussed in the next section. In the subsequent section, we interrogate the current freshwater use planetary boundary using these criteria, which leads to a road map for revising the water planetary boundary. Instead of presenting a new quantitative water planetary boundary, our goal is to provide a scientific road map for the grand challenge of redefining an operable planetary boundary of water. This article suggests subdividing the water planetary boundary by hydrological stores, not into regions. In related companion papers, Gleeson et al.[5] identify the four key functions of freshwater in the Earth System and Zipper et al.[46] describe how to integrate the water planetary boundary with water management from local to global scales. Gleeson et al.[5] provide a significant discussion of hydrological process understanding and proposed methodologies that are intentionally excluded herein. Zipper et al.[46] clearly articulate a cross-scale approach to use the water planetary boundary in subglobal settings defined by physical features, political borders, or commercial entities; here, therefore, we focus on the global scale.

Since planetary boundaries and water in the Earth System are broad and interdisciplinary topics, we narrow our scope to focus on terrestrial and atmospheric freshwater while acknowledging the vital role of oceans; for clarity, "water" refers herein to terrestrial and atmospheric 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.[55] Marine systems and water quality and temperature are related to other planetary boundaries such as ocean acidification, biogeochemical flows, climate change, and novel entities. In the planetary boundary framework, water quality is part of the biogeochemical flows boundary and adding it as part of the water planetary boundary would cause direct and unnecessary duplication, which would lead to more confusion than clarity. 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 "water planetary boundary" and "water planetary sub-boundaries." Below we identify multiple sub-boundaries based on different stores in the water cycle, which we refer to as "[store] water sub-boundary" (e.g., frozen water sub-boundary or surface water sub-boundary). In this article we refer to "water planetary boundary" as the collective of sub-boundaries. We use the term "freshwater use planetary boundary" or "planetary boundaries" only to refer to the current definition presented in Rockström et al.,[1,6] Gerten et al.,[2] and Steffen et al.[3] We consider this the most intuitive terminology since, if we call each of the stores a boundary without any modifier (for example, frozen water planetary boundary), it would potentially lead to confusion when aggregating or visualizing them in combination with the other planetary boundaries.

Interrogating the Current Freshwater Use Planetary Boundary

Earlier discussions have criticized the definition of the freshwater use planetary boundary for a number of reasons, which include (1) scale—water problems are often considered only at local to regional scales, whereas the metric is global which some consider misleading;[52] (2) aggregation—the planetary boundary currently sums streamflow fluxes, but the best way to summarize diverse local impacts to a global metric is not clear;[56] (3) control variable—blue water use is not a biophysical variable representing the complexity of the water cycle and human water modifications;[5,54] (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;[52] (5) underestimation of water use—the global consumptive use of freshwater may be higher due to possible additional or larger effects from irrigation and flow regulation,[45,54] although rebutted by Gerten et al.;[51] and (6) the planetary boundary tends to disregard conditions of local overuse of water resources and may provoke the thought that all usable water can be accessed.[57]

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. This framework could be used for other planetary boundaries in the future and significantly clarifies and expands on the original set of criteria proposed by Rockström et al.[1] for identifying useful control variables for planetary boundaries, which were (1) the variable is universally applicable for the subsystems linked to that boundary; (2) it can function as a robust indicator of process change; and (3) 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 useful for operationalization, 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.

Detailed Interrogation of the Current Planetary Boundary for Freshwater Use

We evaluated the previously proposed freshwater use planetary boundary based on these criteria and found that none of the existing versions and different attempts to subdividing it fully meet any of the evaluation criteria (Table 1). First, while Rockström et al.[1,6] and Gerten et al.[2] 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 of 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

Table 1. Evaluating the Current Planetary Boundaries for Water Use and Different Approaches to Subdividing the Water Planetary Boundaries

Criteria	Rockström et al.[1,6]	Gerten et al.[2]	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 (∼4,000 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 sections on setting and using water planetary sub-boundaries
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
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 section on setting water planetary sub-boundaries
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[54]	+/– see column to the left	– unclear what would be directly measured	+ potentially measurable; see sections on setting and using water planetary sub-boundaries
5. Understandable and operationalizable	+/– 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 on using water planetary sub-boundaries
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
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 column to the left; although more directly interacts with biosphere integrity planetary boundary through environmental flow requirements	+/– see column to the left	+/– for interactions (and potential overlaps with other planetary boundaries); see Figure 1
Total criteria met	0/7	0/7	0/7	3/7

Each criterion is qualitatively evaluated as *met* (+), *not met* (–), or *ambiguous or uncertain* (+/–). Criteria are summed for comparison with tables although any single one is not considered more or less important. The study by Steffen et al.[3] is not included because it effectively re-stated the top-down (Rockström et al.[1,6]) and bottom-up (Gerten et al.[2]) calculations.

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 that remains within environmental flow limits.

Third, consumptive blue water use does not fully capture water's complex interactions with other major Earth System components. While multiple, simultaneously occurring regional environmental flow transgressions could potentially contribute to the transgression of the biosphere integrity planetary boundary and thus indirectly affect 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.[2] and the basin-scale boundary of Steffen et al.[3]), it is unclear whether transgressions in all basins should be treated equally or if some regions contribute disproportionately to the role played by water in maintaining biosphere integrity.

Fourth, while one argument for the current freshwater use 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 the uncertainty of water withdrawal data as well as the important distinctions between water withdrawals, consumptive use, and water use.[58] Furthermore, different approaches to quantify consumptive blue water use tend to produce conflicting estimates,[38,54,59–61] 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 and Destouni[54] 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. Rockström et al.[1,6] note that the crucial importance of green water flows for ecosystems in the original planetary boundary papers 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 because 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.[52] 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 water management. Thus, for the revised planetary boundary to have any practical value for water management, it will be necessary to apply it at local to regional scales (for further details on possible disaggregation methods to integrate the water planetary boundary with existing water management and governance, see our companion paper by Zipper et al.[46]). Any such downscaled global boundaries, however, 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 provide 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 metrics[2] largely fail to represent the inherently local nature of water problems and provide only a partial perspective. The freshwater use planetary boundary has some overlap with other planetary boundaries, especially that for land-system change, which is often associated with changes in water fluxes, highlighting the fact that boundaries interact but also suggesting some redundancy in current definitions of planetary boundaries.

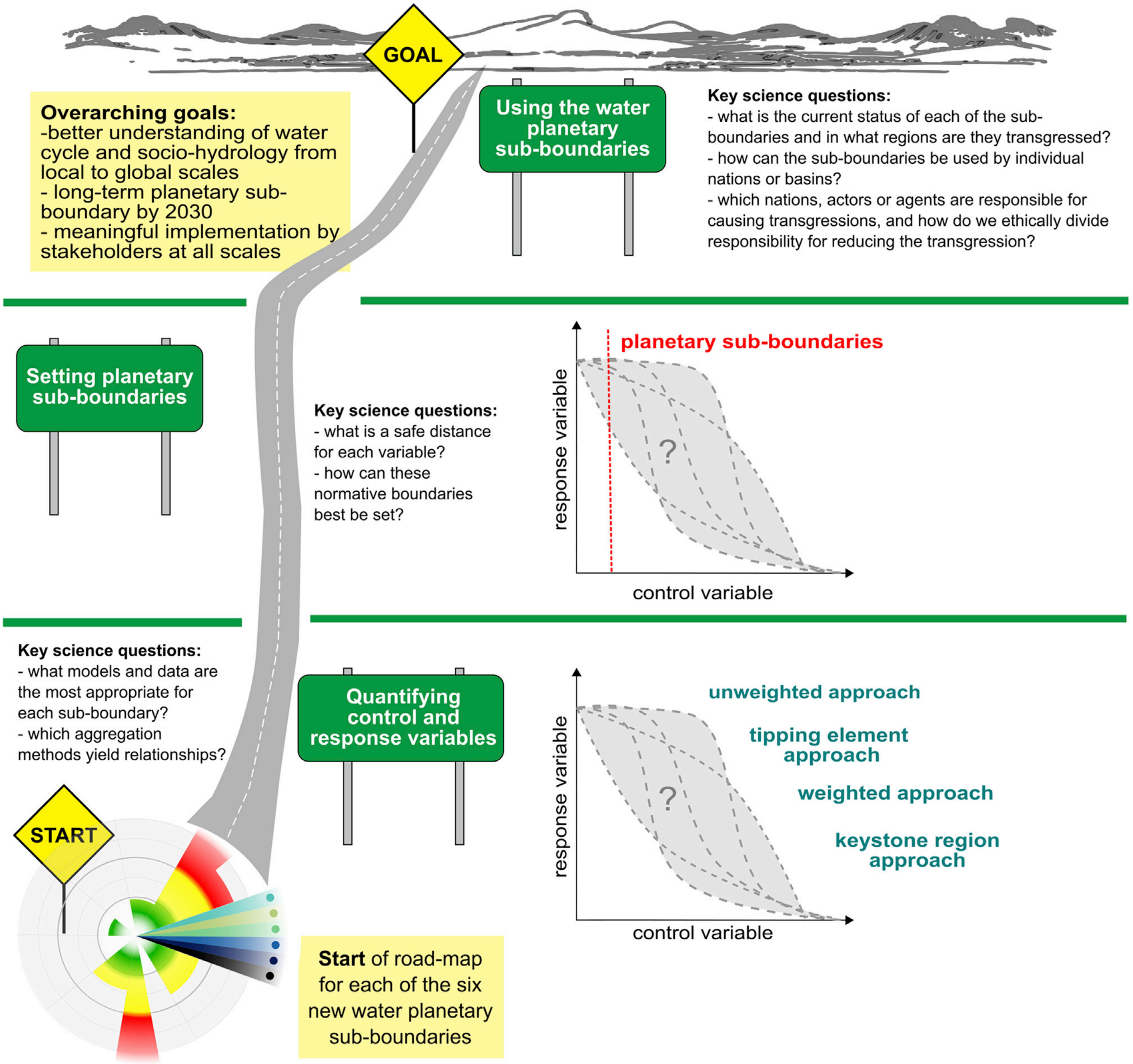
Road Map for Revising the Water Planetary Boundary

Dividing the Current Planetary Boundary into Planetary Sub-boundaries

The current freshwater use planetary boundary needs to be replaced, since it does not meet any of the criteria as described in the previous section. We propose a new road map for revising the water planetary boundary (Figure 3).

We suggest that 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 at different temporal and spatial scales. In our companion paper, Gleeson et al.[5] describe in detail four key functions of freshwater in the Earth System and the functions of each of five major water stores, as shown in Figure 1C. Using these four key functions, we argue for a subdivision of the water planetary boundary based on five water stores: atmospheric water, surface water, soil moisture, groundwater, and frozen water. This approach is physically based and could directly use hydrological models and data, making it quantifiable as well as understandable to hydrologists and non-hydrologists (Table 1). By dividing the water cycle into these five stores, we do not imply that different stores do not interact but rather that water's role in Earth System stability requires maintaining all of the interconnected parts of the water cycle, 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 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 (listed below and shown in Figure 4). For each store, we considered the most important processes that met the largest number of evaluation criteria (listed in the previous section) and most holistic representation of the crucial functions of water in the Earth System.[5] We argue that a division into these sub-boundaries is necessary because these stores operate at different spatiotemporal scales and are important to different Earth System components. We opted to include two planetary sub-boundaries for atmospheric water to incorporate



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?

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

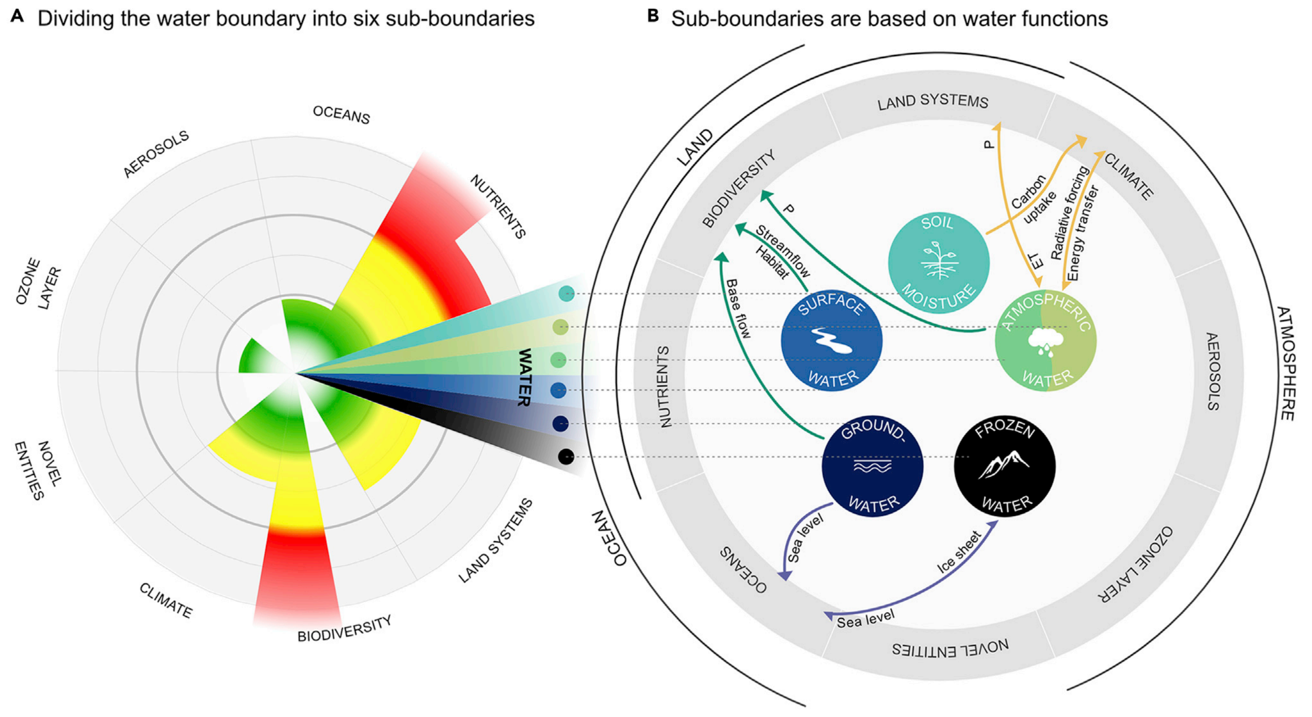
Start of road-map for each of the six new water planetary sub-boundaries

Figure 3. A Road Map for Developing the New Water Planetary Sub-boundaries As Described in the Text

both its hydroclimatic (evapotranspiration regulating climate) and hydroecological (precipitation supporting biodiversity) functions. The Earth System function and process (in italics) addressed by each of the proposed sub-boundaries are highlighted in Figure 4 and summarized below.

- Atmospheric water (hydroclimatic regulation) focuses on *evapotranspiration*, which is important to climate pattern stability or land-atmosphere coupling stability.
- Atmospheric water (hydroecological regulation) focuses on *precipitation*, which 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*, which maintains aquatic biodiversity.
- Groundwater focuses on *baseflow*, which is important to aquatic biodiversity.
- Frozen water focuses on *ice sheet volume*, which is important to sea level rise in the oceans.

Possible scale of analysis, response variables, and interim planetary boundary are compiled in Table 2. 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; four different



A Dividing the water boundary into six sub-boundaries

B Sub-boundaries are based on water functions

Figure 4. Revising the Water Planetary Boundary to Include Six Potential Water Planetary Sub-boundaries
(A) Overview of a possible future planetary boundary 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. Modified from Gleeson et al.;[5] see source for more information.

aggregation methodologies are outlined in Gleeson et al.[5] 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." It is important to note that we suggest moving away from human water use as a metric, since the foundation of the planetary boundary framework is the Earth System and, in the case of water, the Earth System functions of water. Therefore, we argue that the stores of the water cycle are the most important way of conceptualizing the water planetary boundary.

Our preliminary evaluation of the six possible future planetary sub-boundaries for water shows that they are more measurable, understandable, and operational, and potentially represent both regional and global impacts (Table 1). The new sub-boundaries overlap with each other because of complex interactions and feedbacks within the water cycle. 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[3] (see Box 1). 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. However, the "land-system change" boundary, which considers only intact forest biomes, does not adequately represent the hydroclimatic function covered by our proposed sub-boundaries. The sub-boundaries interact substantially, but do not overlap, with the "biogeochemical flows," "novel entities," and "atmospheric aerosol loading" boundaries through the transport function of the sub-boundaries related to surface water and atmospheric water. The suggested sub-boundaries have no overlaps with "stratospheric ozone depletion" and "ocean acidification" given the limited interactions.

As defined above, the "water planetary boundary" refers to a collective of sub-boundaries for each store, and in the future we foresee two possible collectives of sub-boundaries. First, the water planetary boundary could refer to the collective of six sub-boundaries that we describe above. Alternatively, a simpler collective of just two sub-boundaries may be possible: (1) a "green water" sub-boundary combining or considering the two atmospheric water sub-boundaries and the soil moisture sub-boundary; and (2) a "blue water" sub-boundary combining or considering the surface water and groundwater sub-boundaries. In the second approach, frozen water may be considered a derivative of the climate change planetary boundary and therefore excluded. The latter, simpler "water planetary boundary" may be useful if the methods are not successful for some of the individual six sub-boundaries or if simplicity of communication is paramount. The value of these two approaches will be investigated in the future as the methods are applied to each of the sub-boundaries. In addition, the decomposition of the water planetary boundary may be a useful model for other planetary boundaries.

Setting Water Planetary Sub-boundaries

Gleeson et al.[5] address important methodological questions of scale and input data and suggest four different methods of spatial analysis to quantify the relationship between control and response variables. The process of setting fully elaborated

Table 2. Suggestions for Key Aspects of Each of the Six Sub-boundaries including Possible Interim Planetary Boundary Based on Paris Agreement 2°C Target for Late This Century

	Atmospheric Water (Hydroclimate)	Atmospheric Water (Hydroecology)	Soil Moisture (Hydroclimate)	Surface Water (Hydroecology)	Groundwater (Hydroecology)	Frozen Water (Storage)
Possible scale of analysis	distributed hydrological unit	biomes or hydroclimatic regimes	biomes or land cover groups	large basins or river networks	regional aquifers	global
Possible response variables	climate pattern stability or land-atmosphere coupling stability	terrestrial biosphere integrity	carbon uptake or net primary productivity	aquatic biosphere integrity (species richness or species/area)	terrestrial or aquatic biosphere integrity	sea level rise
Possible interim planetary boundary	percentage of global land area with evapotranspiration change within range of simulated future	percentage of global land area with precipitation change within range of simulated future	maintenance of global net primary productivity at or above levels under simulated future	percentage of basins or total river length within environmental flow limits under simulated future	percentage of basins with low flows meeting or exceeding simulated future	volume of ice melt to keep sea level within limits under simulated future

The key Earth System functions of water for each sub-boundary are identified in parentheses (such as hydroecology for surface water).

planetary sub-boundaries with clearly defined relationships between control and response variables for the different water stores may take a considerable amount of time. Nevertheless, there is significant interest in using the water planetary boundary; therefore, we propose setting interim planetary sub-boundaries based on global normative standards for carbon and existing global data (Table 2). 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 United Nations Framework Convention on Climate Change Paris Agreement. In other words, these are the water boundaries that would arise if global carbon governance actors considered water impacts. 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, and the role of water for food, energy, and health are often significant considerations in the Intergovernmental Panel on Climate Change reports.

More specifically, interim sub-boundaries could be calculated using existing global hydrological models and the ''unweighted approach'' described by Gleeson et al.[5] 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 Agreement target of 2°C or less corresponds to RCP 4.5, which does not project global temperature change stabilization until around 2100. 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 of surface water, the control variable could be the ''percentage area of large basins that meet environmental flow requirements'' from ~1950 to ~2100. 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 calculating these interim planetary boundaries, we suggest not attempting to identify the functional relationships between control and response variables (Figure 2). 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, and their interim nature should be clearly communicated in both scientific and policy analyses to avoid confusion.

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 regional and local scales at which water is managed, such as basins or individual nations,[14,62,63] areas governed by multinational organizations such as the European Union,[13] or a company's supply chain.[10] Here, we only briefly introduce how the water planetary boundary may be integrated with existing water management and governance occurring at regional and local scales, which is the main focus of the companion paper by Zipper et al.[46] Previous attempts at downscaling the planetary boundaries have largely focused on calculating a country's ''fair share'' of the global safe operating space (Figure 2). Häyhä et al.[12] 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) socioeconomic considerations, which define the environmental impact a country has both inside and outside of its borders[64]—global accounting methods such as the water footprint[38] are tools for addressing this dimension, although regional opportunity costs need to be considered;[65] and (3) ethical considerations, which address differences 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 fair shares, the water planetary boundary can be operationalized at these disaggregated spatial levels by developing locally relevant boundaries 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, 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 local safe operating space could be defined that is scientifically consistent with the global methodology.[66] 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,[29] while the atmospheric water sub-boundary would require considering the region's precipitationshed.[26]

Conclusions

To transparently investigate 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 boundary 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.[46] Thus, despite the well-founded criticism of the current freshwater use planetary boundary, we argue that the framework 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 analyses, and iteratively updated as science (for the biophysical aspects) and society (for the normative aspects) evolve. We developed a framework for evaluating the water planetary boundary that could be used to evaluate other planetary boundaries as well, such as land use or biodiversity loss, whose critical transitions start at the regional and local scales.
3. 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 road map 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 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 toward fully elaborated planetary sub-boundaries.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

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REFERENCES

1. Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S.I., Lambin, E., Lenton, T., Scheffer, M., Folke, C., Schellnhuber, H.J., et al. (2009). Planetary boundaries: exploring the safe operating space for humanity. Ecol. Soc. *14*, https://doi.org/10.5751/ES-03180-140232.
2. Gerten, D., Hoff, H., Rockström, J., Jägermeyr, J., Kummu, M., and Pastor, A.V. (2013). Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. Curr. Opin. Environ. Sustain. *5*, 551–558.
3. Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., et al. (2015). Planetary boundaries: guiding human development on a changing planet. Science *347*, https://doi.org/10.1126/science.1259855.
4. Oki, T., and Kanae, S. (2006). Global hydrological cycles and world water resources. Science *313*, 1068–1072.
5. Gleeson, T., Wang-Erlandsson, L., Porkka, M., Zipper, S.C., Jaramillo, F., Gerten, D., et al. (2020). Illuminating water cycle modifications and Earth System resilience in the Anthropocene. Water Resour. Res. https://doi.org/10.1029/2019WR024957.
6. Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., et al. (2009). A safe operating space for humanity. Nature *461*, 472–475.
7. Galaz, V., Biermann, F., Folke, C., Nilsson, M., and Olsson, P. (2012). Global environmental governance and planetary boundaries: an introduction. Ecol. Econ. *81*, 1–3.
8. Raworth, K. (2017). Doughnut Economics: Seven Ways to Think like a 21st-Century Economist (Chelsea Green Publishing).
9. Leach, M., Raworth, K., and 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, International Social Science Council., ed. (UNESCO), pp. 84–89.
10. Clift, R., Sim, S., King, H., Chenoweth, J.L., Christie, I., Clavreul, J., Mueller, C., Posthuma, L., Boulay, A.-M., Chaplin-Kramer, R., et al. (2017). The challenges of applying planetary boundaries as a basis for strategic decision-making in companies with global supply chains. Sustainability *9*, 279.
11. Campbell, B., Beare, D., Bennett, E., Hall-Spencer, J., Ingram, J., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J., and Shindell, D. (2017). Agriculture production as a major driver of the Earth system exceeding planetary boundaries. Ecol. Soc. *22*, https://doi.org/10.5751/ES-09595-220408.
12. Häyhä, T., Lucas, P.L., van Vuuren, D.P., Cornell, S.E., and Hoff, H. (2016). From Planetary Boundaries to national fair shares of the global safe operating space—how can the scales be bridged? Glob. Environ. Change *40*, 60–72.
13. Häyhä, T., Cornell, S.E., Hoff, H., Lucas, P., and van Vuuren, D. (2018). Operationalizing the Concept of a Safe Operating Space at the EU Level—First Steps and Explorations (Stockholm Resilience Centre).
14. Cole, M.J., Bailey, R.M., and New, M.G. (2014). Tracking sustainable development with a national barometer for South Africa using a downscaled "safe and just space" framework. Proc. Natl. Acad. Sci. U S A *111*, E4399–E4408.
15. Rockström, J., Falkenmark, M., Folke, C., Lannerstad, M., Barron, J., Enfors, E., Gordon, L., Heinke, J., Hoff, H., and Pahl-Wostl, C. (2014). Water Resilience for Human Prosperity (Cambridge University Press).
16. Konar, M., Evans, T.P., Levy, M., Scott, C.A., Troy, T.J., Vörösmarty, C.J., and Sivapalan, M. (2016). Water resources sustainability in a globalizing world: who uses the water? Hydrological. Process. *30*, 3330–3336.
17. Montanari, A., Young, G., Savenije, H.H.G., Hughes, D., Wagener, T., Ren, L.L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., et al. (2013). "Panta Rhei—everything flows": change in hydrology and society—the IAHS scientific decade 2013-2022. Hydrological. Sci. J. *58*, 1256–1275.

18. Brown, C.M., Lund, J.R., Cai, X., Reed, P.M., Zagona, E.A., Ostfeld, A., Hall, J., Characklis, G.W., Yu, W., and Brekke, L. (2015). The future of water resources systems analysis: toward a scientific framework for sustainable water management. Water Resour. Res. *51*, 6110–6124.
19. Sivapalan, M., Savenije, H.H., and Blöschl, G. (2012). Socio-hydrology: a new science of people and water. Hydrological Process. *26*, 1270–1276.
20. Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, C.A., Wescoat, J.L., and Rodríguez-Iturbe, I. (2014). Socio-hydrology: use-inspired water sustainability science for the Anthropocene. Earths Future *2*, 225–230.
21. Wagener, T., Sivapalan, M., Troch, P.A., McGlynn, B.L., Harman, C.J., Gupta, H.V., Kumar, P., Rao, P.S.C., Basu, N.B., and Wilson, J.S. (2010). The future of hydrology: an evolving science for a changing world. Water Resour. Res. *46*, https://doi.org/10.1029/2009WR008906.
22. Oki, T., Yano, S., and Hanasaki, N. (2017). Economic aspects of virtual water trade. Environ. Res. Lett. *12*, 044002.
23. Porkka, M., Kummu, M., Siebert, S., and Flörke, M. (2012). The role of virtual water flows in physical water scarcity: the case of central Asia. Int. J. Water Resour. Dev. *28*, 453–474.
24. Allan, J.A. (1998). Virtual water: a strategic resource. Ground Water *36*, 545–547.
25. Wang-Erlandsson, L., Fetzer, I., Keys, P.W., van der Ent, R.J., Savenije, H.H.G., and Gordon, L.J. (2018). Remote land use impacts on river flows through atmospheric teleconnections. Hydrol. Earth Syst. Sci. *22*, 4311–4328.
26. Keys, P.W., Ent, R.J.van der, Gordon, L.J., Hoff, H., Nikoli, R., and Savenije, H.H.G. (2012). Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. Biogeosciences *9*, 733–746.
27. Tóth, J. (1963). A theoretical analysis of groundwater flow in small drainage basins. J. Geophys. Res. *68*, 4795–4812.
28. Gleeson, T., and Manning, A.H. (2008). Regional groundwater flow in mountainous terrain: three-dimensional simulations of topographic and hydrogeologic controls. Water Resour. Res. *44*, https://doi.org/10.1029/2008WR006848.
29. Fan, Y. (2019). Are catchments leaky? Wiley Interdiscip. Rev. Water *6*, e1386.
30. Schaller, M.F., and Fan, Y. (2009). River basins as groundwater exporters and importers: implications for water cycle and climate modeling. J. Geophys. Res. *114*, https://doi.org/10.1029/2008JD010636.
31. Vörösmarty, C.J., Hoekstra, A.Y., Bunn, S.E., Conway, D., and Gupta, J. (2015). Fresh water goes global. Science *349*, 478–479.
32. Falkenmark, M., and Rockstrom, J. (2006). The new blue and green water paradigm: breaking new ground for water resources planning and management. J. Water Resour. Plann. Manag. *132*, 129–132.
33. Smakhtin, V.U., Revenga, C., and Döll, P. (2004). A pilot global assessment of environmental water requirements and scarcity. Water Int. *29*, 307–317.
34. Alcamo, J., Flörke, M., and Märker, M. (2007). Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrological Sci. J. *52*, 247–275.
35. Falkenmark, M. (1989). The massive water scarcity now threatening Africa: why isn't it being addressed? Ambio *18*, 112–118.
36. Brauman, K.A., Richter, B.D., Postel, S., Malsy, M., and Flörke, M. (2016). Water depletion: an improved metric for incorporating seasonal and dry-year water scarcity into water risk assessments. Elem. Sci. Anth. *4*, https://doi.org/10.12952/journal.elementa.00008.
37. Kummu, M., Guillaume, J.H.A., De Moel, H., Eisner, S., Flörke, M., Porkka, M., Siebert, S., Veldkamp, T.I.E., and Ward, P.J. (2016). The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. Sci. Rep. *6*, 38495.
38. Hoekstra, A.Y., and Mekonnen, M.M. (2012). The water footprint of humanity. Proc. Natl. Acad. Sci. U S A *109*, 3232–3237.
39. Wada, Y., Gleeson, T., and Esnault, L. (2014). Wedge approach to water stress. Nat. Geosci. *7*, 615–617.
40. Pacala, S., and Socolow, R. (2004). Stabilization wedges: solving the climate problem for the next 50 Years with current technologies. Science *305*, 968–972.
41. Weiskel, P.K., Vogel, R.M., Steeves, P.A., Zarriello, P.J., DeSimone, L.A., and Ries, K.G., III (2007). Water use regimes: characterizing direct human interaction with hydrologic systems. Water Resour. Res. *43*, W04402.
42. Gordon, L.J., Steffen, W., Jönsson, B.F., Folke, C., Falkenmark, M., and Johannessen, Å. (2005). Human modification of global water vapor flows from the land surface. Proc. Natl. Acad. Sci. U S A *102*, 7612–7617.
43. Gleick, P.H., and Palaniappan, M. (2010). Peak water limits to freshwater withdrawal and use. Proc. Natl. Acad. Sci. U S A *107*, 11155–11162.
44. Bhaduri, A., Bogardi, J., Siddiqi, A., Voigt, H., Vörösmarty, C., Pahl-Wostl, C., Bunn, S.E., Shrivastava, P., Lawford, R., and Foster, S. (2016). Achieving sustainable development goals from a water perspective. Front. Environ. Sci. *4*, 64.
45. Destouni, G., Jaramillo, F., and Prieto, C. (2012). Hydroclimatic shifts driven by human water use for food and energy production. Nat. Clim. Change *2*, 1–5.
46. Zipper, S.C., Jaramillo, F., Wang-Erlandsson, L., Cornell, S.E., Gleeson, T., Porkka, M., Häyhä, T., Crépin, A.-S., Fetzer, I., and Gerten, D. (2019). Integrating the water planetary boundary with water management from local to global scales. Earths Future *8*, https://doi.org/10.1029/2019EF001377.
47. D'Almeida, C., Vörösmarty, C.J., Hurtt, G.C., Marengo, J.A., Dingman, S.L., and Keim, B.D. (2007). The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. Int. J. Climatol. *27*, 633–647.
48. Miguez-Macho, G., and Fan, Y. (2012). The role of groundwater in the Amazon water cycle: 1. Influence on seasonal streamflow, flooding and wetlands. J. Geophys. Res. Atmospheres *117*.
49. Nobre, A.D. (2014). The Future Climate of Amazonia (Articulación Regional Amazônica).
50. Rockström, J. (2017). Interactive comment on "HESS opinions: A planetary boundary on freshwater use is misleading" by Maik Heistermann. Hydrol. Earth Syst. Sci. Discuss. https://doi.org/10.5194/hess-2017-112-SC5.
51. Gerten, D., Rockström, J., Heinke, J., Steffen, W., Richardson, K., and Cornell, S. (2015). Response to Comment on "Planetary boundaries: guiding human development on a changing planet. Science *348*, 1217.
52. Heistermann, M. (2017). HESS Opinions: a planetary boundary on freshwater use is misleading. Hydrol. Earth Syst. Sci. *21*, 3455–3461.
53. Sivapalan, M. (2017). Interactive comment on "HESS Opinions: a planetary boundary on freshwater use is misleading" by Maik Heistermann. Hydrol. Earth Syst. Sci. Discuss. https://doi.org/10.5194/hess-2017-112-SC1.
54. Jaramillo, F., and Destouni, G. (2015). Comment on "Planetary boundaries: guiding human development on a changing planet. Science *348*, 1217.
55. Richter, B.D., Mathews, R., Harrison, D.L., and Wigington, R. (2003). Ecologically sustainably water management: managing river flows for ecological integrity. Ecol. Appl. *13*, 206–224.
56. Jaramillo, F., and Destouni, G. (2015). Local flow regulation and irrigation raise global human water consumption and footprint. Science *350*, 1248–1251.
57. Molden, D. (2009). Planetary boundaries: the devil is in the detail. Nat. Clim. Change *1*, 116–117.
58. Gleick, P.H. (2003). Water use. Annu. Rev. Environ. Resour. *28*, 275–314.
59. Siebert, S., Burke, J., Faures, J.M., Frenken, K., Hoogeveen, J., Döll, P., and Portmann, F.T. (2010). Groundwater use for irrigation—a global inventory. Hydrol. Earth Syst. Sci. *14*, 1863–1880.
60. Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., and Schaphoff, S. (2008). Agricultural green and blue water consumption and its influence on the global water system. Water Resour. Res. *44*, W09405.
61. Postel, S.L., Daily, G.C., and Ehrlich, P.R. (1996). Human appropriation of renewable fresh water. Science *271*, 785–788.
62. Dao, Q.-H., Peduzzi, P., Chatenoux, B., De Bono, A., Schwarzer, S., and Friot, D. (2015). Environmental Limits and Swiss Footprints Based on Planetary Boundaries (UNEP/GRID-Geneva & University of Geneva).
63. Lucas, P., and Wilting, H. (2018). Using Planetary Boundaries to Support National Implementation of Environment-Related Sustainable Development Goals: Background Report (PBL Netherlands Environmental Assessment Agency).
64. MacDonald, G.K., Brauman, K.A., Sun, S., Carlson, K.M., Cassidy, E.S., Gerber, J.S., and West, P.C. (2015). Rethinking agricultural trade relationships in an era of globalization. BioScience *65*, 275–289.
65. Kahil, T., Parkinson, S., Satoh, Y., Greve, P., Burek, P., Veldkamp, T.I., Burtscher, R., Byers, E., Djilali, N., and Fischer, G. (2018). A continental-scale hydroeconomic model for integrating water-energy-land nexus solutions. Water Resour. Res. *54*, 7511–7533.
66. Dearing, J.A., Wang, R., Zhang, K., Dyke, J.G., Haberl, H., Hossain, Md.S., Langdon, P.G., Lenton, T.M., Raworth, K., Brown, S., et al. (2014). Safe and just operating spaces for regional social-ecological systems. Glob. Environ. Change *28*, 227–238.