

# 1 The water planetary boundary: interrogation and revision

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## 37 Key points:

- 38 ● The water planetary boundary is a compelling concept that could motivate and improve our  
39 understanding and management of water cycle in the Earth System
- 40 ● The current planetary boundary for freshwater use should be replaced since it does not  
41 adequately represent the role of water in influencing critical Earth System functions

- 42 • A road map towards a new water planetary boundary suggests how to move towards setting six  
43 new water planetary sub-boundaries.

## 44 **Abstract**

45 The planetary boundaries framework has proven useful for many global sustainability contexts, but is  
46 challenging to apply to freshwater, which is spatially heterogeneous, part of complex socio-ecological  
47 systems and often dominated by local dynamics. To date, the planetary boundary for water has been  
48 simplistically defined by as the global rate of blue water consumption, functioning as a proxy for water  
49 partitioning in the global hydrological cycle, and considering impacts on rivers' environmental flow  
50 requirements. We suggest the current planetary boundary should be replaced since it does not  
51 adequately represent the influence of water in critical Earth System functions such as regional climate  
52 and biodiversity. We review the core functions of water in the Earth System and set out a roadmap  
53 towards a more robust, holistic, and locally applicable water planetary boundary. We propose defining  
54 the boundary using four core functions of water (hydroclimatic regulation, hydroecological regulation,  
55 storage, and transport) in conjunction with five water stores (surface water, atmospheric water, soil  
56 moisture, groundwater and frozen water). Through the functions, the stores are inextricably  
57 interconnected with the atmosphere, land, ocean and biosphere. The roadmap outlined here suggests  
58 how to move towards setting six new water planetary sub-boundaries. This ambitious scientific and  
59 policy Grand Challenge that could substantially improve our understanding and management of water  
60 cycle modifications in the Earth System and provide a complementary approach to existing water  
61 management tools.

## 62 **Plain language summary (<200 words)**

63 The planetary boundaries framework proposes quantified guardrails to human perturbation of global  
64 environmental processes that regulate the stability of the planet, safeguarding a Holocene-like status of  
65 the Earth System, and has been widely adopted in sustainability science, governance, and corporate  
66 management. However, the planetary boundary for human freshwater use has been applied much less.  
67 It is based on a global sum of the average annual surface water use from rivers, reservoirs, lakes, and  
68 aquifers. This measure does not reflect all types of human interference with the complex global water  
69 cycle and Earth System. We suggest that the water planetary boundary will be more scientifically robust  
70 and more useful in decision-making frameworks if it is redesigned to consider more specifically how  
71 climate and living ecosystems respond to changes in the different forms of water on Earth: atmospheric  
72 water, soil moisture, groundwater and frozen water, as well as surface water. This paper provides an  
73 ambitious scientific roadmap to define a new water planetary boundary consisting of sub-boundaries  
74 that account for a variety of changes to the water cycle.

## 75 **1. The challenges and possibilities of a water planetary boundary**

### 76 **1.1 The current planetary boundary for freshwater use**

77 The current 'freshwater use' planetary boundary, one of nine planetary boundaries, is based on  
78 allowable human blue water consumptive use (Figure 1). The planetary boundaries, a global  
79 environmental sustainability framework for identifying critical transitions or tipping points in the  
80 complex, interacting Earth, based on control and response variables (Figure 2; see Box 1 for an overview

81 of the planetary boundary concept). The control variable for the current freshwater use planetary  
82 boundary has been set at 4,000 km<sup>3</sup>/year blue water consumption, the lower limit of a 4,000 - 6,000  
83 km<sup>3</sup>/year range that is considered a danger zone as 'it takes us too close to the risk of blue and green  
84 water induced thresholds that could have deleterious or even catastrophic impacts on the earth system'  
85 (Rockström et al., 2009b). Rockström et al. (2009b) suggested blue water consumptive use as a proxy  
86 variable because it functionally integrates the three largest anthropogenic manipulations of the water  
87 cycle: human impacts on precipitation patterns, modifications of soil moisture by land use and land  
88 cover; and water withdrawals from discharge for human use; it was not intended to be an explicit  
89 variable implying that water use can or should be aggregated to global scales. Focusing on water  
90 withdrawals, Gerten et al. (2013) proposed quantifying the boundary by assessing the amount of  
91 streamflow needed to maintain environmental flow requirements in all river basins on Earth, which  
92 suggests a freshwater use planetary boundary in the range of 1,100-4,500 km<sup>3</sup>/year.

93 While the planetary boundary framework garnered interest from international bodies such as  
94 the United Nations (Leach et al., 2013) as well as from the corporate sustainability sector (Clift et al.,  
95 2017), the water planetary boundary has seen limited uptake in water resource management, policy,  
96 and governance. A number of jurisdictions have estimated their local contributions to the water  
97 planetary boundaries (Campbell et al., 2017; Cole et al., 2014; Häyhä et al., 2016, 2018), though it is not  
98 clear that these exercises have led to concrete policy outcomes. In turn, the water planetary boundary is  
99 often not included in global assessments of water and the environment. This lack of uptake is likely due  
100 to the conceptual and methodological over-simplifications of the current freshwater use planetary  
101 boundary, which raises the fundamental question of the relevance or value of a water planetary  
102 boundary for environmental governance, and for water management, specifically.

## 103 **1.2 The relevance of a water planetary boundary for water management and environmental** 104 **governance, and our understanding of socio-hydrologic systems across scale**

105 Water has been identified as one of the planetary boundaries highlighting the critical role water  
106 has in the functioning and stability of the Earth system and that water is fundamentally inextricable  
107 from other parts of the Earth System and other planetary boundaries. The 'raison d'être' for the concept  
108 of a water planetary boundary lies in the need for humanity to consider and govern the multiple, critical  
109 roles water has in the functioning and stability of the Earth System, and the habitability of Earth for  
110 humankind (Rockström et al., 2014). Defining a water planetary boundary could be part of the large and  
111 growing field of water resource management, which addresses the constantly evolving nexus of  
112 hydrology, society, and economics (Konar et al., 2016; Montanari et al., 2013; Sivapalan et al., 2012,  
113 2014; Wagener et al., 2010). Adding a simplified aspirational metric to the toolbox does not suggest that  
114 spatial heterogeneity of water issues be ignored or local-scale data or metrics be superseded. The water  
115 planetary boundary is useful because it serves a distinct and complementary purpose to other water  
116 resources management methods, tools and frameworks in four ways:

- 117 ● Considering water flows beyond traditional basin boundaries. Research on virtual water flows  
118 (Oki et al., 2017; Porkka et al., 2012), moisture transfer (Keys et al., 2012; Wang-Erlandsson et  
119 al., 2018) and regional groundwater flow (Gleeson & Manning, 2008; Tóth, 1963) together  
120 suggest that basin-scale approaches could be complemented by, and nested within approaches  
121 and metrics at scales beyond basins and even to global scales (Vörösmarty et al., 2015).
- 122 ● Acknowledging that all water cycle flows and stocks are important to humanity and the Earth  
123 System, rather than just blue water flows and stocks, which are often the focus of water  
124 resource management for water supply, flood control and aquatic habitat management  
125 (Falkenmark & Rockstrom, 2006). Expanding the focus on water cycle dynamics, the interactions

126 between water cycle and other Earth System components, and the dependence of the  
127 terrestrial biosphere (including human societies) on green water more holistically and  
128 realistically represent the complex interactions between humanity and the water cycle.

- 129 ● Providing an assessment of the ‘safe operating space’ for humanity (Box 1). Various water  
130 management indicators measure impact and status such as water stress (Alcamo et al., 2007;  
131 Falkenmark, 1989; Smakhtin et al., 2004), water depletion (Brauman et al., 2016), water scarcity  
132 (Brauman et al., 2016; Kummu et al., 2016), water footprints (Hoekstra & Mekonnen, 2012),  
133 water wedges (Wada et al., 2014), water use regimes (Weiskel et al., 2007), human  
134 appropriation of evapotranspiration (Gordon et al., 2005; Postel et al., 1996), and hydroclimatic  
135 separation (Destouni et al., 2012). These could be complemented by information about the  
136 proximity of unwanted state shifts.
- 137 ● Recognizing that all members of the global community are stakeholders in local-to-regional scale  
138 functioning of the water cycle. Eventually, disaggregating the water planetary boundary to a  
139 specific basin or jurisdiction could yield results and concerns for managers, policy makers or  
140 stakeholders that are different than those raised by local-to-regional scale water resource  
141 management indicators. The continental-to-global perspective could, for example, highlight the  
142 importance of the water cycle of the Amazon rainforest for climate change (D’Almeida et al.,  
143 2007; Miguez-Macho & Fan, 2012), monsoon system, and agricultural production outside the  
144 region through teleconnections and indirect impacts (Nobre, 2014). This could lead to the  
145 recognition of the global community’s role as stakeholder in the Amazon rainforest water cycle  
146 beyond the regional and national scale.

### 147 1.3 Objectives, scope and terminology

148 **Our objective is interrogating and reframing the water planetary boundary to reflect complex,**  
149 **interconnected and heterogeneous freshwater processes in the Earth System.** This work is based on  
150 multiple workshops, working groups and intense collaboration and debate. First, we review how the  
151 planetary boundaries are defined and identified (Box 1) which forms a basis for a new set of criteria for  
152 evaluating the current freshwater use planetary boundary (Section 2). We interrogate the current  
153 freshwater use planetary boundary using this criteria, which leads to road map for revising the water  
154 planetary boundary (Section 3). Instead of presenting a new quantitative water planetary boundary, our  
155 goal is to provide a scientific roadmap for the Grand Challenge of redefining an operable planetary  
156 boundary of water. By holistically and transparently evaluating the value, concerns, and possibilities of  
157 water planetary boundaries, we aim to move the debate forward, in response to recent discussions  
158 (Gerten et al., 2015; Heistermann, 2017; Jaramillo & Destouni, 2015; Rockström, 2017; Sivapalan, M.,  
159 2017). In related papers, Gleeson et al. (submitted) identify the four key functions of freshwater in the  
160 Earth System and Zipper et al. (submitted) describe how to integrate the water planetary boundary with  
161 water management from local to global scales.

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

171 We use the term 'freshwater use planetary boundary' only to refer to the current definition presented in  
172 Rockström et al., (2009a,b), Gerten et al. (2013) and Steffen et al. (2015).

173

**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 world development on planet Earth that remains in a manageable Holocene-like inter-glacial state (Figure 2). 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., 2015).

Nine planetary boundary processes and systems have been identified. For each boundary process/system, a control variable 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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)

174

## 175 **2. Interrogating the current freshwater use planetary boundary**

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

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

196

197 **Scientific criteria**

- 198 1) Planetary boundary variables: Are the proposed control and response variables clearly defined  
199 and related? Is there a clear basis for a planetary boundary value?  
200 2) Regional impacts and upscaling mechanisms: Is there evidence for regional impacts, and  
201 plausible mechanisms by which regional impacts could scale to global impacts?  
202 3) Impacts on Earth System stability: Is there evidence that this process impacts Earth's stability,  
203 directly or indirectly through interactions with core planetary boundaries?  
204

205 **Scientific representation criteria:**

- 206 4) Measurable: Can the status of the control variable be measured, tracked in time, and  
207 monitored?  
208 5) Understandable and operational: Is the planetary boundary broadly understandable to non-  
209 scientific audiences and potentially operational?  
210 6) Represents regional and global impacts: Does this planetary boundary represent both regional  
211 and global impacts? Is this representation consistent with the social perceptions of impacts?  
212 7) Uniqueness: Are the processes or impacts uniquely represented by this planetary boundary, or  
213 is there overlap and redundancy with other planetary boundaries?  
214

215 Criteria 1–3 are fundamental requirements of any planetary boundary, as they address scientific  
216 evidence of mechanisms, especially relating to Earth's 'Holocene-like' state. Criteria 4) and 5) are  
217 necessary for operationalisation and criteria 6) and 7) address the usefulness of a planetary boundary by  
218 ensuring that representation of impacts can resonate with social concerns and policy prioritizations and  
219 that redundancy in the planetary boundary framework is limited.  
220

221 **Detailed interrogation of the current planetary boundaries for freshwater use**

222 We evaluated the already proposed planetary boundaries for water based on these criteria and  
223 find that none of them fully meet any of the evaluation criteria (Table 1). First, while Rockström et al.  
224 (2009a, 2009b) and Gerten et al. (2013) both defined control variable limits, neither clearly defined the  
225 response variable, nor the relationship between control and response variables.

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

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

244 Fourth, while one argument for the current water planetary boundary might be a control  
245 variable that is simple, measurable and understandable, consumptive blue water use is in fact  
246 notoriously challenging to estimate due to uncertainty in statistics of water withdrawals (Vörösmarty et  
247 al., 2000). Furthermore, different approaches to quantify consumptive blue water use tend to produce  
248 conflicting estimates (e.g., Hoekstra and Mekonnen, 2012; Siebert and Döll, 2010; Rost et al., 2008;  
249 Jaramillo and Destouni, 2015) and separating anthropogenic blue and green consumptive use from  
250 natural fluxes requires complex water resource modeling. Additionally, there has been significant  
251 debate on what to include in and how to perform calculations of consumptive water use. For instance,  
252 Jaramillo & Destouni (2015) propose that green water and its human-driven changes should be taken  
253 into account directly, and that doing so would lead to the planetary boundary for freshwater use already  
254 being transgressed. While Rockström et al. note the crucial importance of green water flows for  
255 ecosystems in the original planetary boundary papers (2009a, 2009b), it is not reflected in the proposed  
256 control variable in a meaningful quantitative way.

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

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

### 279 **3. A road map for reframing the water planetary boundary**

#### 280 **3.1 Dividing the current planetary boundary into planetary sub-boundaries**

281 The current the current freshwater use planetary boundary needs to be replaced since it does  
282 not meet any of the criteria as described in Section 2. We suggest the water planetary boundary must be  
283 subdivided to more realistically represent the complexity and heterogeneity of the water cycle and how  
284 it interacts with the various components of the Earth System (Figure 1c) at various time and space  
285 scales. Gleeson et al. (submitted) describe in detail the four key functions of freshwater in the Earth  
286 System and the functions of each of the five water stores. We argue for a subdivision based on water  
287 stores: atmospheric water, surface water, soil moisture, groundwater and frozen water. This approach is



288 physically based and could directly use hydrologic models and data, making it more measurable as well  
289 as understandable to hydrologists and non-hydrologists (Table 1). By dividing the water cycle into these  
290 five stores, we do not imply that different stores do not interact, as illustrated in Figure 1b. An  
291 alternative division, based on the Earth System functions of water (hydroclimatic regulation,  
292 hydroecological regulation, storage, and transport) would represent the core functions directly, but it  
293 adds complexity, as different components of the Earth System may have the same core function (i.e.  
294 hydroclimatic regulation through albedo control by clouds, glaciers, and inland surface waters).

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

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

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

322 Our preliminary evaluation of the six possible future planetary sub-boundaries for water shows  
323 that they are more measurable, understandable, operational and potentially represent both regional  
324 and global impacts. However, they require refinement through extensive community efforts because,  
325 while there is generally strong evidence of regional impacts, robustness of upscaling mechanisms and  
326 impacts on Earth System stability are variable (Box 3). The new sub-boundaries overlap with each other  
327 and with other planetary boundaries because of complex interactions and feedbacks within the water  
328 cycle. Overlap with planetary boundaries of climate change and biosphere integrity is expected, as these  
329 are suggested to be the 'core' boundaries through which the others operate (see section 1; Steffen et al.  
330 2015). Similarly, some degree of overlap with other sub-boundaries is inevitable because of the complex  
331 interactions and feedbacks within the water cycle. The sub-boundaries for evapotranspiration and soil  
332 moisture further overlap with the land-system change boundary, which also focuses on climate-

333 regulating processes in land systems but, we argue, does not adequately represent the hydroclimate  
334 function covered by our proposed sub-boundaries.

### 335 **3.2 Setting water planetary sub-boundaries**

336 Gleeson et al. (submitted) address important methodological questions of scale and input data  
337 as well as suggest four different methods of spatial analysis to quantify the relationship between control  
338 and response variables (bottom of Figure 4). The process of setting ‘fully elaborated’ planetary sub-  
339 boundaries with clearly defined relationships between control and response variables for the different  
340 water stores may take a considerable amount of time (at least ~5-10 years, comparable to other global  
341 change science synthesis activities). Yet there is significant interest in using the water planetary  
342 boundary so we explored setting interim planetary sub-boundaries based on global normative standards  
343 for carbon and existing global data. Interim planetary boundaries for water could be set by quantifying  
344 the change in proposed control variables for each water component under the Representative  
345 Concentration Pathways (RCP) with related emissions and land use scenarios consistent with the  
346 UNFCCC Paris Agreement (Figure 4). In other words, these are the water boundaries that would arise if  
347 global carbon governance actors considered water impacts. The discussions and decision-making of  
348 climate change agreements, such as the Paris agreement are based in part on impacts to water systems.  
349 For example, water security, floods, droughts are often significant considerations in the IPCC reports.

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

### 365 **3.3 Using the water planetary sub-boundaries**

366 For the water planetary boundary to have practical value for water management, it needs to be  
367 operational and informative at the sub-global scales at which water is managed such as basins,  
368 individual nations (Cole et al., 2014; Dao et al., 2015; Lucas & Wilting, 2018), areas governed by  
369 multinational organizations (Häyhä et al., 2018b), or the footprint of a company’s supply chain (Clift et  
370 al., 2017). Here, we briefly introduce how the water planetary boundary may be used at sub-global  
371 scales, which is the focus of a separate study (Zipper et al., submitted). Previous attempts at  
372 operationalizing the planetary boundaries have largely focused on calculating a country’s ‘fair share’ of  
373 the global safe operating space, (Figure 2). (Häyhä et al., 2016b) identify three key dimensions to  
374 consider: (1) biophysical processes, which define the relevant scale at which the planetary boundary can  
375 be addressed; water cycle processes are spatially heterogeneous so the global impacts of a change  
376 depend on site-specific factors; (2) socio-economic considerations, which define the environmental

377 impact a country has both inside and outside of its borders (MacDonald et al., 2015); global accounting  
378 methods such as the water footprint (Hoekstra & Mekonnen, 2012) are tools for addressing this  
379 dimension although regional opportunity costs need to be considered (Kahil et al., 2018); and (3) ethical  
380 considerations, which address difference among countries in environmental impacts caused by  
381 exceeding the control variable as well as their ability to respond to environmental challenges; equity-  
382 based allocation frameworks could address this dimension.

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

#### 393 **4. Conclusions**

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

- 398 1) The planetary boundary framework could complement existing tools for water resource  
399 management by offering a unique approach for assessing water cycle modifications as part  
400 of the wider human impact on the Earth System (Section 1.2). Thus, despite the well-  
401 founded criticism of the current freshwater use planetary boundary (Section 2), we argue  
402 that the concept of a planetary boundary for water is useful and worth serious intellectual  
403 attention.
- 404 2) Planetary boundaries can and should be evaluated with qualitative and quantitative  
405 analysis, and iteratively updated as science (for the biophysical aspects) and society (for the  
406 normative aspects) evolve. We developed a framework for evaluating water planetary  
407 boundaries (Section 2) that could be used to evaluate other planetary boundaries as well,  
408 especially those that do not have clear global tipping points - such as land use or biodiversity  
409 loss - and whose critical transitions start at the regional and local scales.
- 410 3) The current water planetary boundary does not adequately represent the complex and  
411 interconnected nature of water, and thus it should be replaced. We developed a roadmap  
412 for reframing the planetary boundary for water with new sub-boundaries for each water  
413 component. This encompasses new modeling and analysis and much work in clarifying  
414 tipping points, keystone regions, cross-scale propagation of impacts, and the fundamental  
415 relationship between core Earth System functions of water and other Earth System  
416 components. We suggest that interim planetary sub-boundaries be set while working in  
417 parallel towards fully elaborated planetary sub-boundaries.

418

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420

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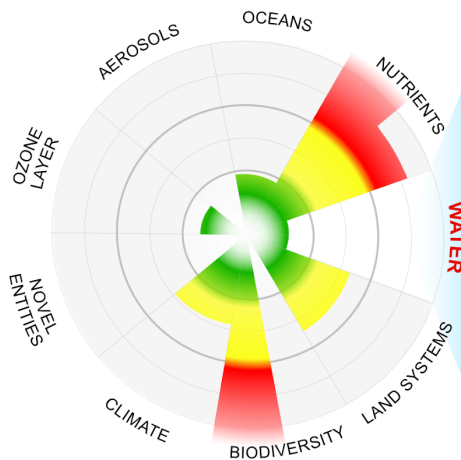
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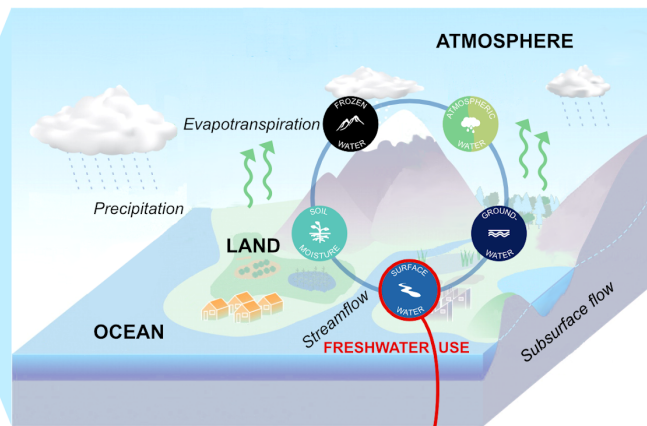
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575

A. Earth System components underlying the current planetary boundaries

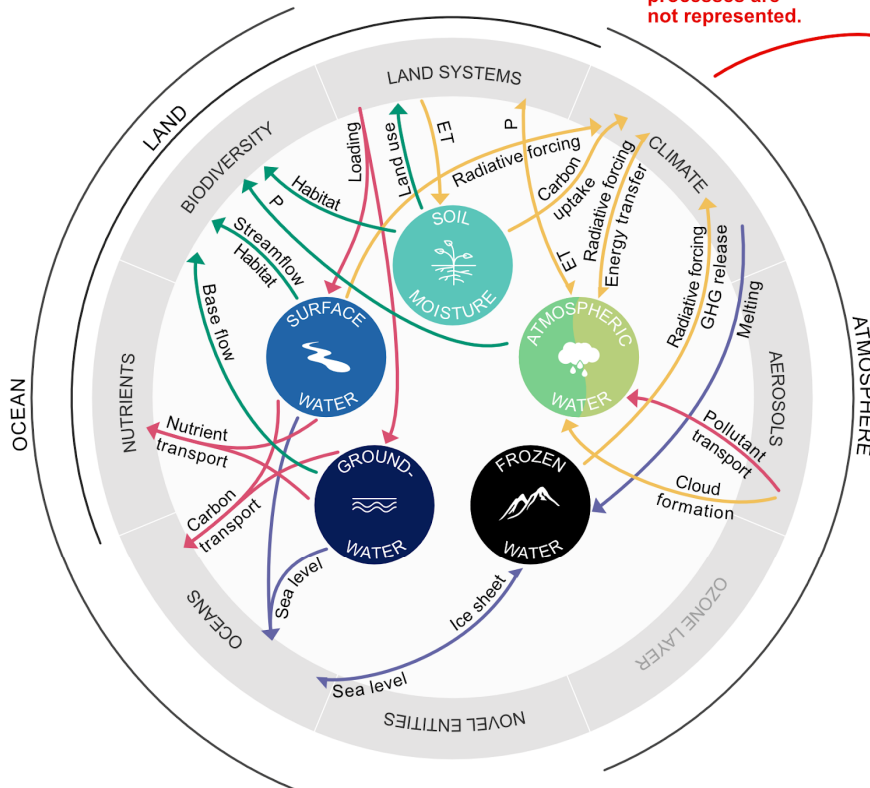


B. Earth System components and stores of water



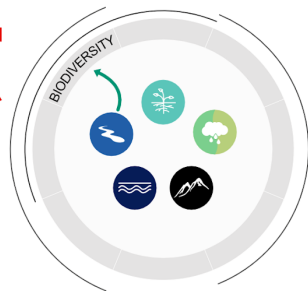
**Current freshwater use planetary boundary only considers streamflow impacts on aquatic biodiversity.**

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



**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

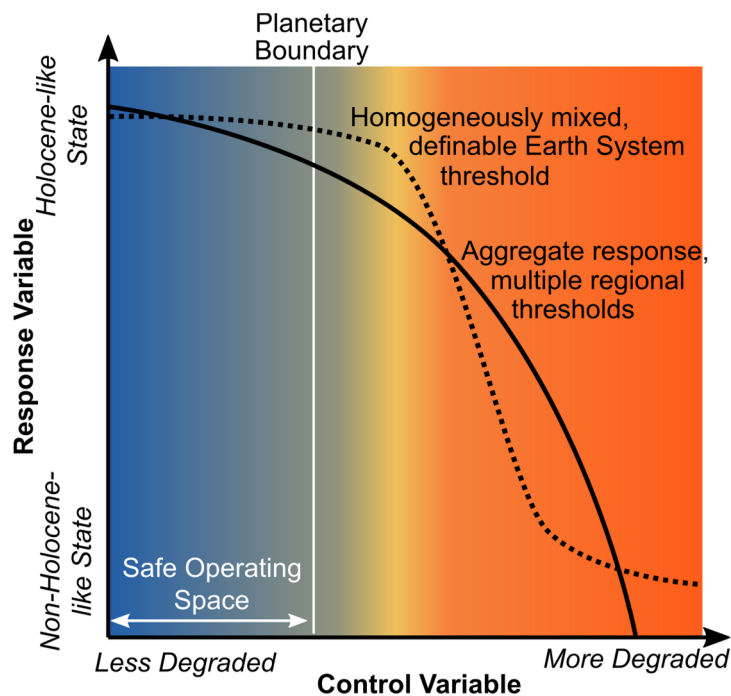
- Hydroclimatic regulation
- Hydroecologic regulation
- Storage
- Transport

PROCESSES

- One-way interaction
- Two-way interaction



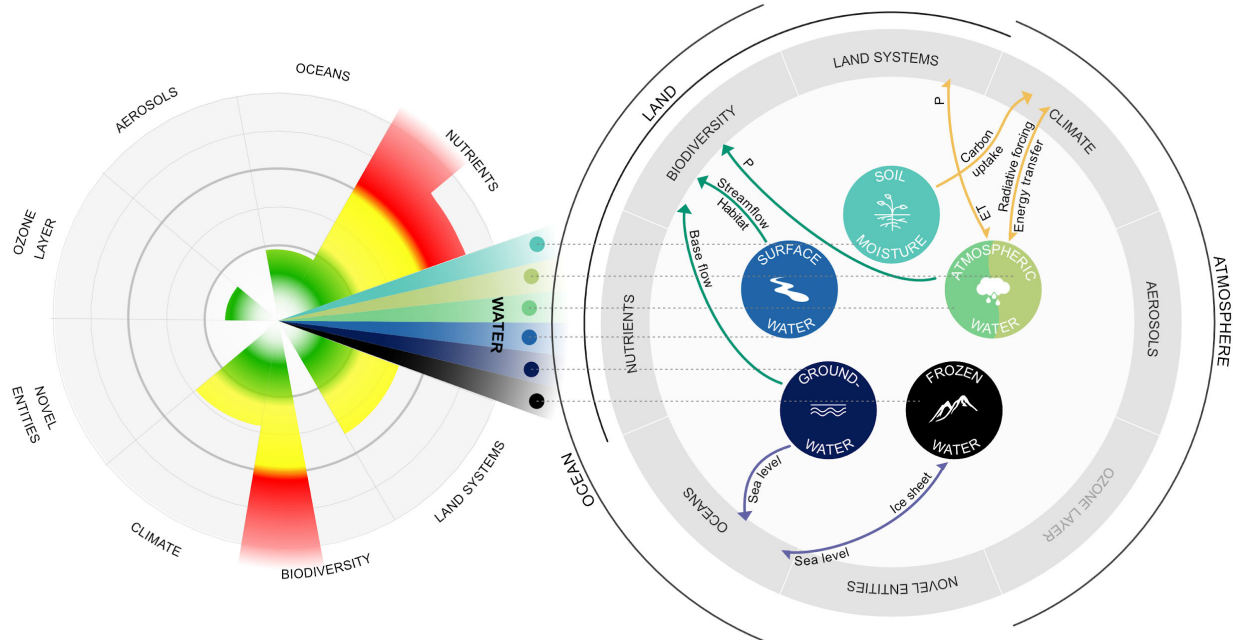
578 Figure 1. Freshwater use is one of the (a) current planetary boundaries, yet affecting only a small component of  
 579 (b) the hydrosphere, which includes numerous stores of water. Since we focus on the near-surface hydrosphere,  
 580 we consider land (part of the lithosphere) and ocean (part of the hydrosphere) as important related Earth  
 581 System components. (c) The core functions of water in the Earth System (larger diagram) and how they are  
 582 represented in the current freshwater use planetary boundary (small diagram). Diagrams show the five stores of  
 583 the freshwater hydrosphere (colored circles in center), major components of the Earth System (outer ring), and  
 584 detailed Earth System components underlying the different planetary boundaries (inner grey ring). The arrows  
 585 denote processes linking the water stores and the Earth System components, color-coded by Earth System  
 586 functions of water (hydroclimate, hydroecology, storage, and transport). Note that in figures, hydroclimatic and  
 587 hydroecological regulation are shorted to hydroclimate and hydroecology; P is precipitation and ET is  
 588 evapotranspiration. Figures (a) and (b) are modified from Steffen et al. (2015) and Oki and Kanae (2006),  
 589 respectively.  
 590



591  
 592 Figure 2. Graphical framework for the definition of the planetary boundaries, showing two types of relationships  
 593 between a control and response variable (modified from Steffen et al., 2015).  
 594

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)
<b>Possible scale of analysis</b>	Precipitation sheds	Biomes or hydroclimatic regimes	Biomes or land cover groups	Large basins or river networks	Regional aquifers	Global
<b>Possible response variable(s)</b>	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
<b>Possible interim planetary boundary</b>	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

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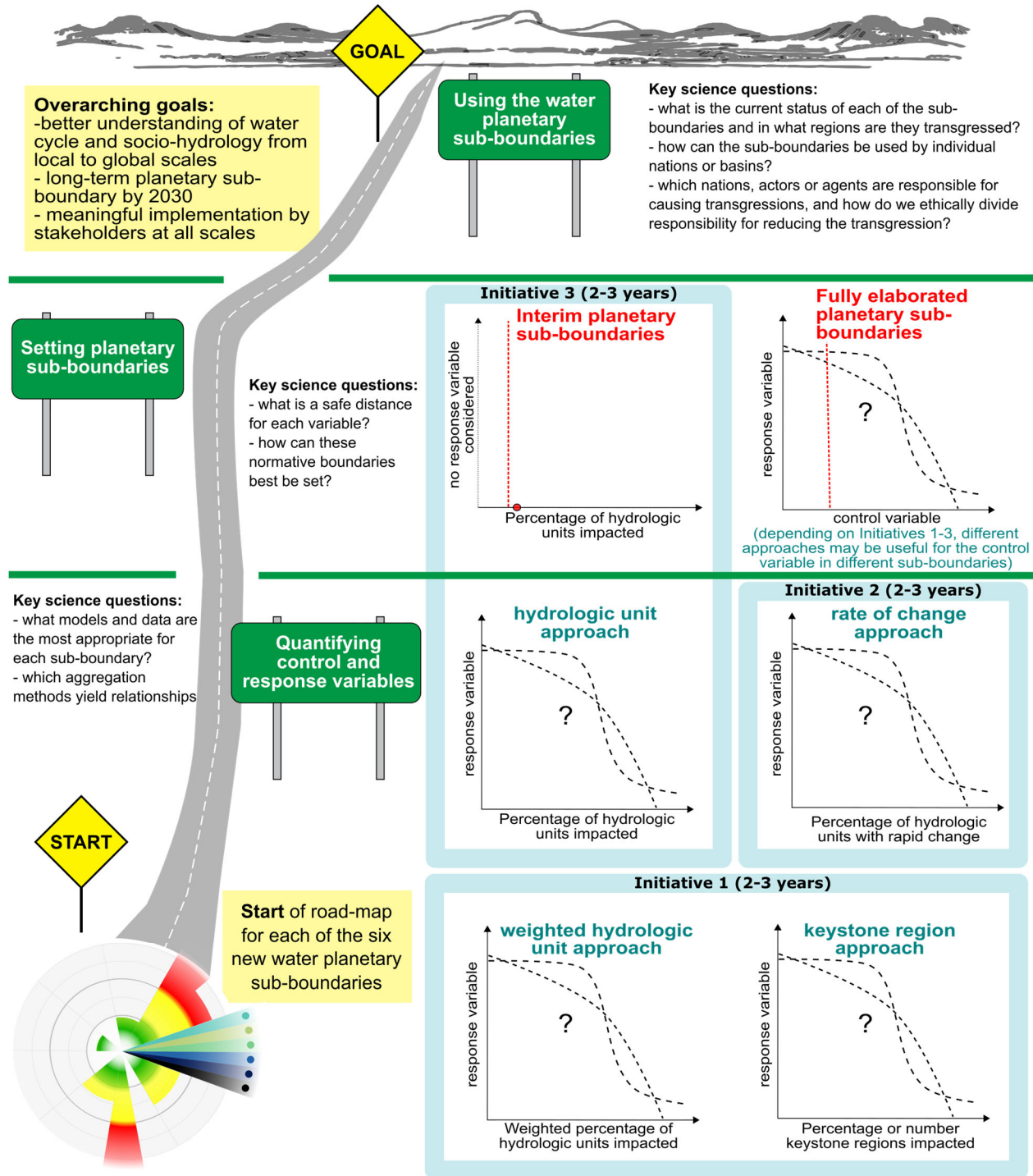
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**Figure 3. Revising the water planetary boundary to include six potential water planetary sub-boundaries. (a) A possible future planetary boundary overview figure with the six divided water stores. (b) Defining water planetary sub-boundaries based 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).**



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

607 **Table 1. Evaluating the current planetary boundaries for water use and different approaches to subdividing the**  
608 **water planetary boundaries. Each criterion is qualitatively evaluated as *met (+)*, *not met (-)* or *ambiguous or*  
609 ***uncertain (+/-)*. Criteria are summed for comparison to tables although any single one is not considered more or**  
610 **less important. Steffen et al. (2015) is not included since they effectively re-stated the top-down (Rockström et**  
611 **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
<b>1) Planetary boundary variables</b>	- Maximum amount of consumptive blue water use considered proxy control variable (~4000 km <sup>3</sup> /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.
<b>2) Regional impacts and upscaling mechanisms</b>	+/- 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.
<b>3) Impacts on Earth System stability</b>	- 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.
<b>4) Measurable</b>	+/- 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.
<b>5) Understandable and operationalizable</b>	+/- 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.
<b>6) Represents regional and global impacts</b>	- 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.
<b>7) Uniqueness</b>	+/- 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.
<b>Total criteria met</b>	<b>0/7</b>	<b>0/7</b>	<b>0/7</b>	<b>3/7</b>