Integrating the water planetary boundary with water management across scales

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Abstract

The planetary boundaries framework defines the ‘safe operating space for humanity’ in terms of nine important global processes influenced by humans which can destabilize the Earth System if perturbed. The planetary boundary for freshwater use attempts to provide a global limit to anthropogenic water cycle modifications, but it has been challenging to translate and apply it to the regional and local scales at which societally relevant water problems and management typically occur. We develop an integrative cross-scale approach considering how the water planetary boundary could help guide sustainable water management and governance at different sub-global contexts defined by physical features (e.g. watershed or aquifer), political borders (e.g. city, nation, or group of nations), or commercial entities (e.g. a corporation, industry or trade group, financial institution). The integration of the water planetary boundary at these sub-global contexts occurs via two approaches: (i) calculating *fair shares*, in which local water cycle modifications are compared to that context’s allocation of the global safe operating space, taking into account biophysical, socio-economic, and ethical considerations; and (ii) defining a *local safe operating space,* in which interactions between water stores and Earth System components are used to define local boundaries required for sustaining the local water system in stable conditions, which we demonstrate with a case study of the Cienaga Grande de Santa Marta wetland complex in Colombia. By harmonizing these two approaches, the water planetary boundary can be used in multiple contexts to ensure that water cycle modifications remain within both local and global boundaries. This provides a broadly applicable method by which the planetary boundaries framework complements existing water management and governance approaches.

1. Local water resources and Earth System stability

Water, the 'bloodstream of the biosphere' (Ripl, 2003), is fundamental to Earth System functioning and human society. Due to the central role of water for maintaining global biosphere integrity, regulating climate, and mediating carbon and nutrient cycling, changes to the water cycle can propagate through the Earth System and disrupt processes interacting across numerous scales. For example, land use change in one setting can alter evapotranspiration and lead to precipitation change downwind (Wang-Erlandsson et al., 2018; Zipper et al., 2019a). Self-amplifying land-water interactions mean that deforestation may lead to regional forest die-back in areas such as the Amazon (Zemp et al., 2017) with potential cascading impacts on Earth System stability as a whole (Steffen et al., 2018). In addition to physical processes, socio-economic factors external to a watershed can impact local hydrological conditions: agriculture, by far the largest user of freshwater, is driven by global socio-economic decisions as crops are shipped all over the world (Dalin et al., 2017; Hoekstra & Mekonnen, 2012; Jaramillo & Destouni, 2015; Marston et al., 2015). Anthropogenic climate change, a global challenge, also has diverse impacts on local water systems (Cook et al., 2018; Pfahl et al., 2017). In other words, the local water cycle is shaped by global processes and modifications to local hydrological processes can have global consequences.

This emerging, integrated understanding of interconnections between local and global water systems requires integrated management and governance strategies across scales (Biermann et al., 2012; Keys et al., 2017; Sivapalan et al., 2014). However, developing generalizable understanding of the spatiotemporal scales spanned by the water cycle has been a longstanding challenge in hydrology, water management, and at their intersection (Blöschl et al., 2019; Blöschl & Sivapalan, 1995; Daniell & Barreteau, 2014; Klemeš, 1983). In particular, recent synthetic work has identified translating understanding of coupled human and natural systems across scales as a key future research priority to provide management-relevant science (Konar et al., 2016; Kramer et al., 2017). While socio-hydrology has been suggested as a potential tool to bridge the gaps between watershed-scale and global-scale water management (Di Baldassarre et al., 2019; Konar et al., 2016), specific approaches for integrating global water sustainability targets with local water management remain lacking.

The planetary boundaries framework, introduced by Rockström et al. (2009) and further elaborated by Steffen et al. (2015), offers one approach to bring a global perspective to local water management (Konar et al., 2016). This framework identifies nine boundaries representing critical Earth System processes that characterise deviation from the relatively stable environmental conditions of the

Holocene, the epoch during which the world's societies have developed. For most of these processes, a quantifiable *control variable* has been suggested, which may cause some *response variable* to depart from relatively stable Holocene-like conditions if sufficiently perturbed, either alone or through interactions with other Earth System processes (Rockström et al., 2009; Steffen et al., 2015). For effective boundary-setting, the control variable should be both quantifiable and subject to influence by human actions, while the response variable should describe Earth's stable conditions and be influenced by the control variable (Gleeson et al., 2019b). For safeguarding each planetary boundary the control variable is set some distance upstream from departure of the response variable from stable conditions, typically at the lower end of uncertainty due to systemic and/or scientific factors (Figure 1). The secure area bounded by the nine planetary boundaries has been referred to as a "safe operating space for humanity" (Rockström et al., 2009) in that it describes the Holocene-like Earth System conditions, which so far are the only ones known in which human civilization has thrived and in which the risk of destabilizing global dynamics is low.

Regarding water - our focus here - the planetary boundary for freshwater use has originally been based on the amount of freshwater needed to maintain rivers' environmental flow requirements (Gerten et al., 2013; Steffen et al., 2015). Recently, Gleeson et al. (2019a, 2019b) proposed a more holistic representation of the various functions of water in maintaining Earth system stability, distinguishing six sub-boundaries relating to the five major stores of freshwater (Table 1). Environmental flow requirements are retained in this approach, together with new water planetary sub-boundaries for frozen water, groundwater, soil moisture, surface water, and two sub-boundaries for different aspects of atmospheric water. Gleeson et al. (2019a, 2019b) suggested potential control and response variables for these new sub-boundaries (Table 1) meant to represent the primary function of water in the Earth System, but a significant program of cross-disciplinary collaborative work remains to select and evaluate appropriate variables and develop suitable methods to aggregate from distributed to global values. To provide a sound societal relevance for these efforts, it is necessary to first determine whether the water planetary boundary can be meaningfully integrated with existing management approaches.

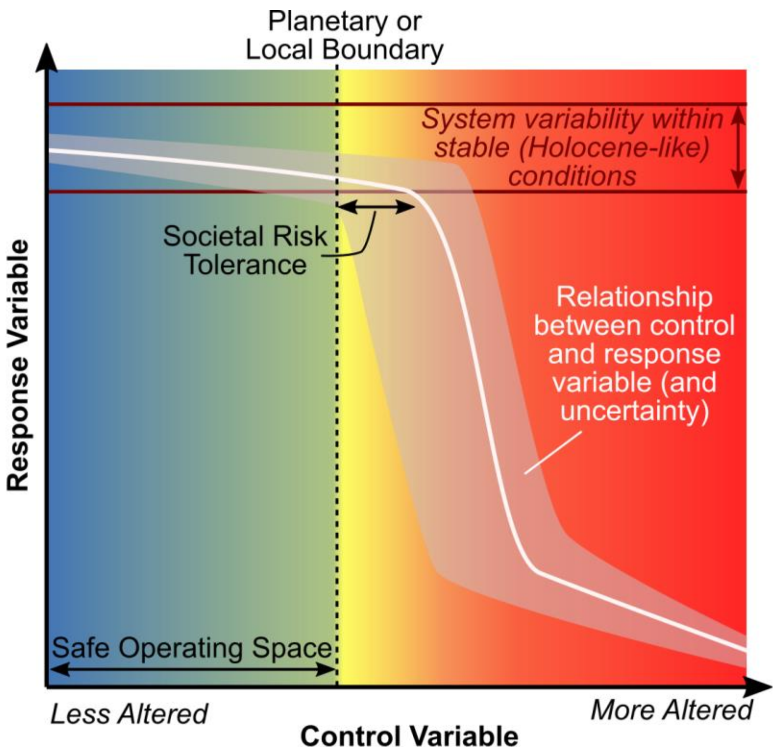

Figure 1. A planetary or local boundary (dashed line) is set where the system shifts from stable to possibly destabilized conditions in response to change in the control variable. Based on (Gleeson et al., 2019b; Rockström et al., 2009; Steffen et al., 2015). A precautionary approach takes into account the system variability of the response variable (dark red horizontal lines), scientific and systemic uncertainty about the relationship between the control and response variables (grey zoning around the white line) and societal tolerance of risk. The relationship between the control and response variable shown here is just one possible relationship, and these relationships are not necessarily threshold-type or even monotonic.

Since there is no global governance nor common organizational institutions for planetary-scale water management and governance (Biermann et al., 2012), the water planetary boundary needs to be translated to the local and regional scales where water management and governance typically operate (CISL, 2019; Downing et al., In review; Konar et al., 2016). In this study, we address three questions necessary to integrate local water management and governance with global water sustainability:

(i) How can global-scale values be meaningfully disaggregated to the diverse spatial scales at which water management and governance occurs such as watersheds, nations, commercial entities?

(ii) How does the planetary boundary framework complement existing water management approaches at each of these spatial scales?

(iii) What scientific questions need to be addressed to move the planetary boundary framework forward as a potential water management approach?

We develop a flexible approach to applying the water planetary boundary across different scales and jurisdictions, in order to complement existing management and governance approaches by accounting for interactions across traditional water system borders and scales and for relationships among different components of the Earth System. The water planetary boundary can be used in sub-global domains defined using physical features (e.g. watershed or aquifer management), political borders (e.g. a city, nation, or group of nations), or commercial entities (e.g. companies, industries, or trade groups operating within or across national borders). As one example, we demonstrate how the water planetary boundary can be used in the context of a degraded hydrological system, the Cienaga Grande de Santa Marta wetland complex, in Colombia. Furthermore, because the water sub-boundaries highlight key interactions between water cycle change, climate change, and land system change, we therefore broaden the term "water management" to refer to not only management of liquid water in surface water and aquifers, but any type of management of Earth System processes that have significant interactions with the water cycle. For brevity, we will use the term 'local contexts' to refer interchangeably to any of these sub-global applications.

2. Principles for using the planetary boundary in sub-global water management

Here, we synthesize previous literature on sub-global use of the planetary boundary framework (Table 2) to classify and explore two approaches, *fair shares* and *local safe operating space*, in order to identify strengths, weaknesses, and principles for effective implementation of each approach. In Section 3, we present a methodology to integrate these two approaches to calculate local harmonized boundaries with strong connections to both global and local water sustainability.

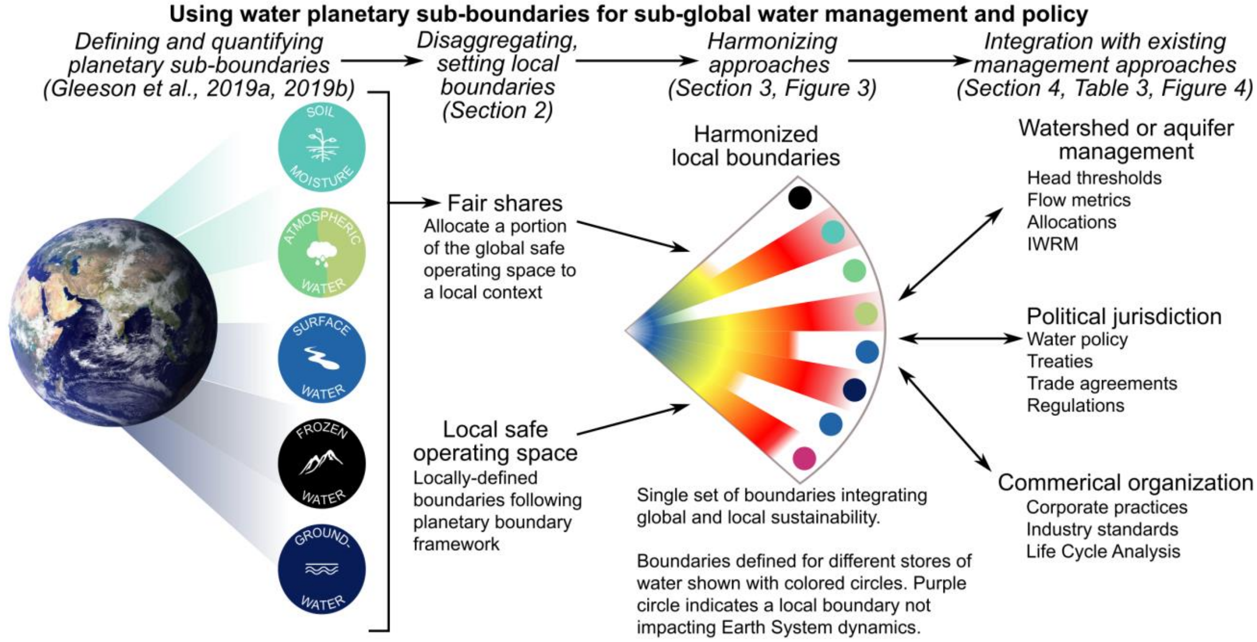

Figure 2. Translating water's planetary role in Earth System dynamics to local management and governance. In the harmonized approach, colored circles indicate a water sub-boundary corresponding to a specific store of water and the red-yellow-blue color gradient corresponds with the current position of the control variable with respect to the boundary, as in Figure 1. The fair shares approach will subdivide each water planetary sub-boundary to the local context. The local safe operating space approach may have local boundaries corresponding to all or some of the sub-boundaries, as well as additional locally-relevant boundaries which may not have an impact on Earth System function. Further details about each step are provided in the text sections and figures referenced in the top of the figure.

2.1 Fair shares approach

The *fair shares* approach is a top-down approach which treats the planetary boundary value of the control variable as a global safe operating space "budget", and then allocates a portion of that global safe operating space to a given local context. The fair shares approach has been used in diverse local contexts including nations, cities, companies and industries (Table 2). This approach has strong global relevance because it is directly connected to the Earth System functions that define the planetary boundaries, but this also means it may have limited local relevance because the globally defined control variable may not be the most effective descriptor or authoritative guidance for modifications of the water system in some local contexts. If global fair shares exceed socially and ecologically important thresholds in local hydrological processes (discussed in Section 2.2), local decision-makers would intervene in the water system well before the global boundary is reached and vice versa.

The fair shares approach requires three steps: (1) setting the planetary boundary value(s); (2) allocating a fraction of the global safe operating space to a local context; and (3) comparing current performance to the allocation (i.e. to the local fair share) for each control variable.

2.1.1 Setting the planetary boundary

The first step in operationalizing the fair shares approach is defining the safe operating space by determining values for each of the water planetary sub-boundaries. While recent work has proposed new planetary sub-boundaries for different stores of water in the Earth system (Gleeson et al., 2019a, 2019b), previous efforts to operationalize the planetary boundaries framework using the fair shares approach have so far all used the control variable and estimated boundary values from Rockström *et al* (2009) and Steffen *et al* (2015) (Table 2). In the case of water, this means that the planetary boundary is typically taken as 4000 km^3 yr^{-1} of consumptive blue water use. To better account for the ecological impacts of human water use, Gerten et al. (2013) suggested a spatially explicit quantification of environmental flow requirements to explicitly focus on the impacts of freshwater use for local biosphere integrity. Using this approach, they calculated monthly environmental flow requirements for all surface water globally, which resulted in a boundary between 1100-4500 km^3 yr^{-1}. Reframing the water planetary boundary for different stores of water as proposed by Gleeson et al. (2019a, 2019b) improves the ability of the fair shares approach to accurately represent water's role in Earth System dynamics, and therefore we suggest that future work on the fair shares approach should shift to these new control and response variables (Table 1).

2.1.2 Allocating the global safe operating space to local contexts

The fair shares approach requires allocating the global safe operating space (for any planetary boundary) to sub-global scales and entities. For commercial organizations, economic indicators are typically used such as a corporation's global market share (Ryberg et al., 2018; Sandin et al., 2015). For political contexts (e.g. nations), allocation of the global safe operating space is most often done using a per capita approach in which the global value of the control variable of the planetary boundary is apportioned based on the number of people living in that nation relative to the global population (Dao et al., 2015; Hoff et al., 2014; Nykvist et al., 2013; O'Neill et al., 2018). The major flaw of per capita allocation is that it allocates a larger portion of the global safe operating space to more populous nations, without taking into account local hydrological factors nor people's capacity to respond to environmental challenges (Häyhä et al., 2018). Alternative allocation principles, for example based on equality, rights, capacities and the responsibility of different groups of people could be used instead (see

Häyhä et al., 2016; Lucas & Wilting, 2018; or the extensive literature on allocating greenhouse gas emissions). Different allocation approaches can result in substantial differences in what counts as a fair share of the global safe operating space (Ryberg et al., 2018; Sandin et al., 2015).

Choosing among allocation approaches requires ethical and political decisions that account for local differences in the contribution to global environmental challenges, the ability to respond to them, and differing definitions of 'fair' among stakeholders (Biermann, 2012; Häyhä et al., 2016). For instance, the suggested control variable for the frozen water sub-boundary is the volume of global ice melt (Table 1), which is strongly driven by polar air temperature increases due to anthropogenic climate change; however, the countries which contribute most to climate change are not the same countries that feel the strongest (downstream) impacts (Althor et al., 2016; Biemans et al., 2019), posing an ethical challenge. Climate change has been found to increase inequality of income distribution between polluting countries and those countries with the least share of pollution responsibility (Diffenbaugh & Burke, 2019). Addressing ethical issues is particularly challenging because different definitions of equity lead to different outcomes (Häyhä et al., 2016; Ryberg et al., 2018). Also, regardless of the allocation approach used, any fair shares approach will be sensitive to the estimated position of the planetary boundary and control variable, both of which may include substantial uncertainty which must be accounted for and communicated as part of the fair shares downscaling.

2.1.3 Comparing current performance to the allocation for each control variable

Previous planetary boundaries applications have used both production-based and consumption-based approaches to calculate a local context's performance relative to the allocation of a local fair share, both of which are originally derived from climate accounting (Table 2). A production-based approach considers impacts of the production of goods and services on the water cycle only within the local context, such as within national territory. However, many environmental impacts (particularly from wealthy nations) are partially externalized via trade (Marston et al., 2015; Wiedmann & Lenzen, 2018) and/or felt in locations distant from where the water use occurs (e.g., transboundary effects; Munia et al., 2016; Veldkamp et al., 2017). A consumption-based approach therefore considers the global impacts on the water cycle associated with the water used to supply all the goods and services consumed within the local context. This is known as embedded or virtual water, and there is growing consensus that it should be accounted for in sustainable resource-use decision making. For example, more than 40% of the water use associated with the supply of products and services to Europe occurs elsewhere (Häyhä et al., 2018), and 11% of global nonrenewable groundwater use is attributable to international trade (Dalin et al., 2017). Geographically explicit approaches such as water footprints can be used for consumption-based quantification (Hoekstra & Mekonnen, 2012; Mekonnen & Hoekstra, 2011; Vanham et al., 2019). Companies and industries, which operate across borders, frequently use consumption-based life cycle analyses, which account for the various materials and impacts of processes required in complex global supply chains, and have begun to integrate the planetary boundaries framework as a lens to interpret the results of life cycle analyses (Brejnrod et al., 2017; Ryberg et al., 2018; Wolff et al., 2017). Life cycle analyses can also use the water footprint approach to quantify the performance of a product, company, or supply chain for water impacts all over the world (Chapagain et al., 2005; Kounina et al., 2013; Pfister et al., 2009). The water footprint can be adjusted based on water scarcity at the location of production, i.e. where the consumptive use takes place, to more directly reflect environmental impacts (Ridoutt & Pfister, 2010), though this is controversial because it introduces additional value choices and non-physical dimensions to the footprint metric (Hoekstra, 2016; Pfister et al., 2017).

Gleeson et al.'s (2019a, 2019b) new control variables will require the development of new approaches for consumption-based quantification. As an example, they suggest that the control variable for atmospheric water's role in hydroclimatic regulation may be the degree of human-caused change in evapotranspiration, for instance due to land use change and water use. The water footprint concept described above offers a way to link different changes in evapotranspiration to specific local actions such as land use change or irrigation (Schyns et al., 2019). Land use footprints and indirect land use change metrics (Searchinger et al., 2008; Weinzettel et al., 2013) can likely be adapted to meet the needs of the fair shares approach for assessing sub-global responsibility. However, these sorts of attribution studies are disputed due to the difficulties involved in tracing how national policies propagate through the global economic system to influence land use (Mathews & Tan, 2009; Zilberman, 2017). Ongoing research aims to make environmental footprints, including land use, more spatially explicit.

2.2 Local safe operating space approach

The *local safe operating space* approach is a bottom-up approach that uses the principles of the planetary boundary framework to generate locally meaningful control variables, response variables, and boundary values defining the local stable conditions of the water system (Figure 1). Local variables may or may not be the same as the planetary boundary control and response variables, because the drivers of hydrological stability in local water systems can differ from drivers of stability at the Earth System scale. This approach allows stakeholders and water managers working on a specific region to define safe operating spaces that have a strong local relevance and can inform efficient water management interventions locally. However, local safe operating spaces potentially have weak relevance at the global scale. Furthermore, while the planetary boundaries were designed as global measures of biophysical Earth System conditions (Rockström et al., 2009; Steffen et al., 2015), local safe operating spaces are more likely to integrate social-environmental considerations regarding the aspects of the water system most important to society (Dearing et al., 2014; Teah et al., 2016).

The local safe operating space approach also typically contains three steps: (1) defining locally meaningful control and response variables, which may differ from the variables used for the planetary boundaries; (2) setting boundary values which defined the local safe operating space; and (3) quantifying the current state of each control variable. These can be connected to the fair shares approach using the harmonization approach presented in Section 3.

2.2.1 Defining the control and response variables

The local safe operating space approach complements the fair shares approach by focusing on the local water system, and there is no explicit relationship to Earth System stability (though local effects may scale up to impact Earth System stability). The definition of locally relevant control and response variables should be based on the biophysical and socio-economic properties of the local water system, which may already be identified in thresholds or allocations from existing water management agreements. Like the planetary boundary control and response variables (Section 1), the control variable should be quantifiable and can be influenced by human actions, while the response variable should describe stable conditions for the local water system and be influenced by the control variable. There may be cases where the control variable is the same in the local safe operating space and fair shares approaches (Section 3).

Past attempts to define local safe operating spaces have typically used consumptive freshwater use, the same control variable as the water planetary boundary (Table 2; Cole et al., 2014; Fanning & O'Neill, 2016; Teah et al., 2016). However, the local safe operating space approach may require alternative or additional control and response variables based on the unique conditions of the local water system context. This flexibility is well-aligned with the multiple water sub-boundaries corresponding to different water stores proposed by Gleeson et al. (2019a, 2019b) in Table 1. For example, in an analysis of regional safe operating spaces for two regions in China, Dearing et al. (2014) did not include a freshwater use boundary because the primary regional water challenges were related to water quality and sedimentation, rather than water quantity. Similarly, environmental flow requirements could be used as a local process of interest. In this way, the local safe operating space can complement existing management approaches.

2.2.2 Setting the local boundary

For operational purposes, setting a boundary value requires a clearly defined relationship between a control variable and the response variable(s), though this was not explicitly defined in the original freshwater use planetary boundary (Rockström et al., 2009; Steffen et al., 2015). In local contexts, the stable conditions of the response variable may be defined using the observed range during the Holocene (as in the planetary boundary for water) or based on some other locally-relevant environmental thresholds. For instance, Dearing et al. (2014) use historical measurements of hydrological and ecological variables in anthropogenically perturbed regions to identify boundary values. Identification of water regime shifts (reviewed in Falkenmark et al., 2019) can be used to define locally-relevant ranges of the response variable and corresponding control variables.

Using the planetary boundary framework to define a local safe operating space has primarily been an academic exercise to date (Table 2), but for practical water management and governance , socio-economic and equity concerns will come into play (Figure 1). During the setting of boundary values, both the characterisation of stable hydrological conditions and assessments of acceptable levels of risk are likely to vary among stakeholders within a community as well as across local contexts. For example, poorer stakeholders may be less resilient to short-term hydrological variability (i.e., define stable conditions as a narrower range in Figure 1) and have fewer options to reduce exposure to risk (i.e., set the boundary further back from estimated thresholds in Figure 1). Community-level involvement has not been prioritized in past efforts to apply the planetary boundaries framework, but from a sustainable development perspective, local boundary setting can be rooted in environmental justice to define a "safe and just operating space" (Dearing et al., 2014; Leach et al., 2013; Raworth, 2012). This would require that all communities within the local context - not just the historically advantaged groups in a position of power - are meaningfully involved in defining the local safe operating space and implementing environmental policies or regulations to maintain the local safe operating space in a manner which is responsive to changes in local conditions driven by external factors such as global climate change (Martín-López et al., 2019).

2.2.3 Quantifying the current value of each control variable

Quantifying the current value of the control variable and comparing it to the local boundary value informs whether the local context is within its local safe operating space. Where data are available to define the relationship between the control and response variables, quantifying the current value of the control variable can be done in a fairly straightforward manner (Cole et al., 2014; Dearing et al., 2014). In many cases, however, data and deep understanding of the system needed to accurately estimate control variable values are lacking for some or all local boundaries. This may provide an opportunity to further integrate local communities in the definition of the local safe operating space, as demonstrated by Teah et al. (2016). In addition to quantifying biophysical limits for a portion of the Heihe River in China, Teah et al. (2016) surveyed local residents on their perceptions on the current status of the control variables and the potential impacts of regional boundary transgression, finding that resident perceptions of the values of the control variables relative to their regional boundaries were mostly consistent with the quantified values. While the social survey was not used to guide the setting of boundaries nor identification of the ecological thresholds, it does indicate that local stakeholder involvement has the potential to both identify relevant control variables, estimate the present value for control variables where monitoring data do not exist, and evaluate the potential impacts of transgression. Where uncertainty in the estimation of the control variable is large, stakeholder involvement may be particularly important to constrain acceptable control and response variable values.

3. Harmonizing approaches to integrate local to global water sustainability targets

3.1 Harmonizing fair shares and local safe operating space approaches

The fair shares and local safe operating space approaches each have benefits and drawbacks. The fair shares approach provides a framework for assessing global responsibility and allocating responsibility for local contribution to global processes; however, it does not provide any guidance for whether the water cycle remains within locally important limits which are the primary concerns of water managers and policymakers. In contrast, the local safe operating space approach addresses local limits to water system modifications, but does not provide any information about potential impacts external to the local context which are essential for global citizenship.

Here, we propose a methodology to harmonize the fair shares and local safe operating space approaches to develop a set of local boundaries which are consistent with both local and global water sustainability. For a given water-related boundary (here defined for each store of water), there are three potential relationships between the fair shares and local safe operating space approaches (Figure 3):

1) *Different stores:* For stores which are relevant in only one of the two approaches, there is no harmonization needed since there will only be a single boundary value. A hypothetical example of this may be that frozen water is unimportant in many tropical catchments so would be ignored in the local safe operating space approach, but is still considered in the fair shares approach due to its impact on global processes. A second hypothetical example may be a locally important store of water - for example, the water level in a lake - which is considered in the local safe operating space approach but makes no significant impact globally so is ignored in the fair shares approach. In this case, the local control variable could be water withdrawals directly from the lake or surface water or groundwater in the lake's contributing area, the response variable could be the aquatic biosphere integrity of the lake, and the local boundary defined based on the change in lake levels which would lead to a collapse of the aquatic food web (AghaKouchak et al., 2015; Kraft et al., 2012). In both these examples,the control variable, response variable, and boundary value from whichever of the two approaches is relevant can be used.
2) *Different control variables:* For stores where there are different core water functions at the local and global scales, the control variables may differ between the fair shares approach (which focuses on global processes) and the local safe operating space approach (which focuses on local processes). Again, a hypothetical example illustrates this. For the groundwater sub-boundary, the primary function of groundwater globally is providing baseflow to rivers during dry periods to maintain environmental flow requirements (Table 1). For the fair shares approach, this suggests a potential control variable of stream-aquifer flux, a response variable of aquatic biosphere integrity, and a boundary value based on global environmental flow requirements (Gerten et al., 2013; Gleeson et al., 2019a, 2019b; Wada et al., 2013). However, in some local contexts there are many groundwater-dependent terrestrial ecosystems, suggesting a potential control variable of groundwater depth below the land surface, a response variable of terrestrial biosphere integrity, and a boundary value when groundwater drops below the rooting depth (Eamus et al., 2015; Qiu et al., 2019; Rohde et al., 2017). For this type of relationship, a harmonized approach would require a unique set of sub-boundaries for this water store, with separate control and response variables for each of the two approaches (i.e., fair share and local safe operating space).

3) *Same control variable:* For stores where the same control variable is used for the local safe operating space and fair shares approaches, the relationship between the control and response variables may not be the same in the two approaches. Modifying our hypothetical example for the groundwater sub-boundary from the previous type, if the control variable is stream-aquifer flux and the response variable is aquatic biodiversity for both the local safe operating space and fair shares approaches, the boundary value may be different in the two approaches if small changes in aquatic biodiversity would push the local socio-environmental system beyond the local safe operating space without having a negative global impact. Where the local safe operating space boundary is lower (more environmentally conservative) than the fair shares boundary, this indicates that prioritizing local management will be consistent with global Earth System stability and therefore this lower value can be used. However, in cases where a fair shares boundary is lower than the local safe operating space boundary indicates that locally acceptable water management practices are problematic when upscaled to the planetary level. In this case, ethical and socio-economic considerations are necessary to reconcile this mismatch between scales (Häyhä et al., 2016), for example by determining whether excessive local impacts can be compensated for by conservation elsewhere at the global scale via trade-off analysis (Section 3.2). In either case, the end result would be a single harmonized boundary. Because the control-response relationship and therefore boundary value may change through time due to changing biophysical conditions and interconnectedness with other non-water-related processes, the relationship between the local safe operating space and fair shares boundary values may change through time.

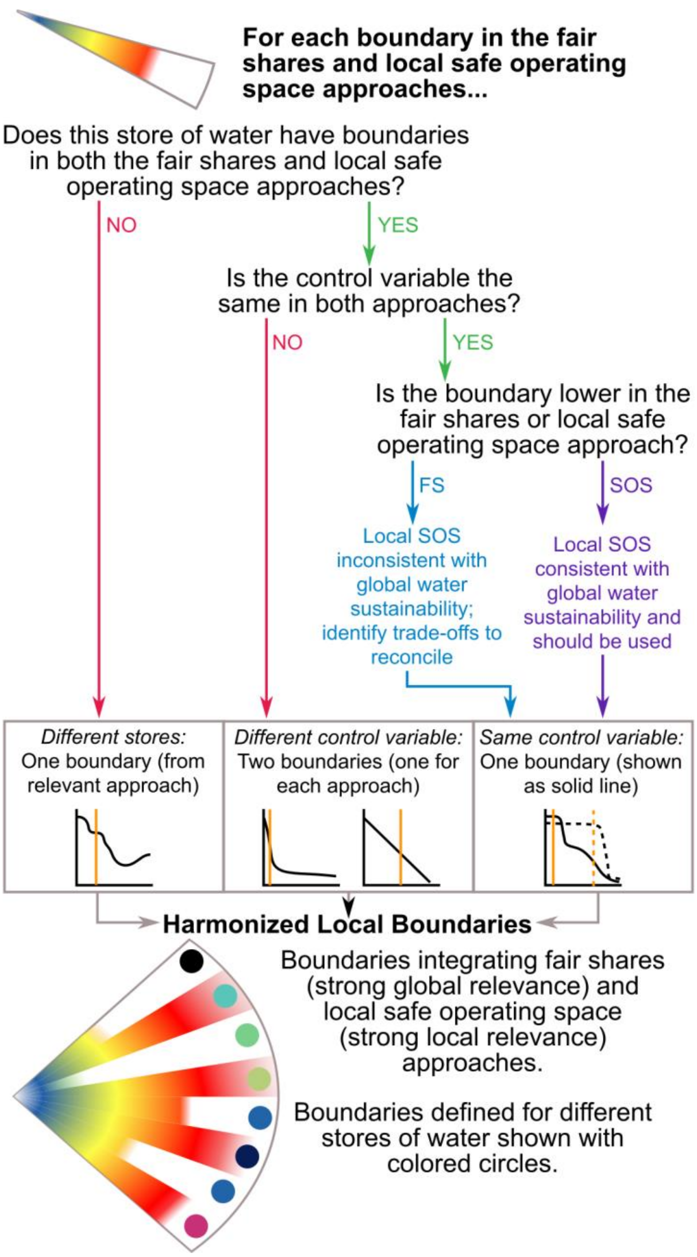

Figure 3. Decision tree for harmonization process between fair shares and local safe operating space approaches. Each sub-boundary in the fair shares and local safe operating space approaches should be evaluated to determine whether a given store of water should have one or two boundaries in the harmonized set. The hypothetical plots corresponding to each type of boundary show the relationship between a control variable (x-axis) and response variable (y-axis) as shown in Figure 1, and the orange line shows the boundary value. Each of the colored circles indicates a water sub-boundary corresponding to a specific store of water from either the fair shares or the local safe operating space approach, as in Figure 2. The red-yellow-blue color gradient corresponds with the current position of the control variable with respect to the boundary, as in Figure 1.

Based on these three types of relationships, the locally harmonized water boundary will always have at least as many sub-boundaries as the water planetary boundary, which may be supplemented by additional sub-boundaries derived from the local safe operating space approach. In this manner, the harmonized local boundaries will always be consistent with both global and local water sustainability goals, and provide a framework for determining whether local water management is consistent with both local socio-environmental processes and global Earth System function. An example of these types of relationships for the Ciénaga Grande de Santa Marta wetland complex (Colombia) is explored in Box 1.

3.2 Recognizing and respecting real-world complexity

Comparison between the local safe operating space and fair shares approaches can provide valuable insight into the cross-scale relationships between sub-global-scale water systems and Earth System function. For instance, Gleeson et al. (2019) suggest that there may be 'keystone regions' where water cycle modifications have a disproportionate impact on Earth System function which manifest as changes in the core planetary boundaries of climate change and biosphere integrity. In keystone regions, we hypothesize that the local safe operating space and fair shares approaches would have similar control and response variables and boundary values, since the degradation of the local water system would lead to outsize impacts at the global scale. The keystone region concept should not be taken to imply that local water cycle modifications with little detectable influence on Earth System stability are unimportant to the water planetary boundary. All local changes contribute to the cumulative effect on the global water cycle, and through the to the pressures on the water and other planetary boundaries, especially the core boundaries of climate change and biosphere integrity. To avoid this unintended consequence of the planetary boundary framework, harmonization with the fair shares approach as described above and existing management and governance approaches is essential. Additionally, countries and organizations in non-keystone regions might also yield a high indirect influence over keystone regions, for example through trade and geopolitics (Bierkens et al., 2019; Dalin et al., 2017; D'Odorico et al., 2019), which can be accounted for in the fair shares approach. Thus, while this paper primarily focuses on disaggregation from global to local scales, comparison between the local safe operating space and fair shares approaches may also be useful for determining appropriate techniques to aggregate from local to global scales (CISL, 2019).

While the typologies presented in Figure 3 are comprehensive of all potential local-global interactions, the complexity of the real world will introduce trade-offs among water sub-boundaries and other planetary boundaries across spatial scales, time scales, degrees of reversibility, stakeholders, and types of environmental impacts (Booth et al., 2016; Heck et al., 2018b; Qiu et al., 2018; Rodríguez et al., 2006). In addition, boundaries in the real-world may not be expressed as two-dimensional plots as shown in Figure 1, but rather as multidimensional parameter spaces representing multiple interconnected ecohydrological processes. As one example, groundwater withdrawals for irrigation may enhance local net primary productivity and food production, but alter regional-scale hydroclimate (spatial scale trade-off; DeAngelis et al., 2010; Harding & Snyder, 2012a, 2012b; Keune et al., 2018), impair groundwater-dependent ecosystems (stakeholder trade-off; Barlow & Leake, 2012; Gleeson & Richter, 2017; Zipper et al., 2018, 2019), and make groundwater resources unavailable for future generations (reversibility and time scale trade-off; Butler et al., 2018; Gleeson et al., 2012; Wada & Bierkens, 2014; Whittemore et al., 2016) and increase cropland at the expense of other ecosystem services or planetary boundaries, such as biodiversity and biochemical flows (environmental impact trade-off; Anache et al., 2019; Foley et al., 2005, 2011; Hanaček & Rodríguez-Labajos, 2018; VanLoocke et al., 2017).

There are numerous existing frameworks, models, and tools for understanding interactions and managing trade-offs with diverse approaches including cluster analysis, integrated (nexus) modelling, multi-criteria analyses, and trade-off curves (Cavender-Bares et al., 2015; Deng et al., 2016; Heck et al., 2018b; Hurford et al., 2014). While it is beyond the scope of this paper to address how the water planetary sub-boundaries can be integrated with existing trade-off analysis tools, we note that managing trade-offs will require a detailed and process-based understanding of interactions among the water sub-boundaries and the rest of the planetary boundaries at local and global scales, and motivates further research on understanding cross-scale feedbacks between local water systems, social-ecological conditions, and the Earth System. To make decisions among local and global trade-offs will inherently be a normative and participatory exercise based on clear visualisation and communication of trade-offs to local stakeholders and decision-makers (see Section 5), and may be a tool to mobilize non-local financial resources as incentive or compensation for foregone local benefits when contributing to global sustainability targets and thus help a region stay within both local and global boundaries. This can follow examples from the climate finance domain such as the Amazon Fund (Forstater et al., 2013; Nakhooda et al., 2013).

4. Opportunities for complementing existing water management approaches

Numerous approaches to water management exist, most of which focus on either surface water or groundwater (Figure 4). In this section, we discuss how, and why, local applications of the water planetary boundary can complement these existing approaches (Table 3; CISL, 2019). Most importantly, the Earth Systems focus of the planetary boundaries demonstrates the necessity of expanding 'water management' beyond the traditional focus on surface water and groundwater to include aspects of land management (related to atmospheric water, precipitation and soil moisture) and climate change governance (related to changes in frozen water and in water availability).

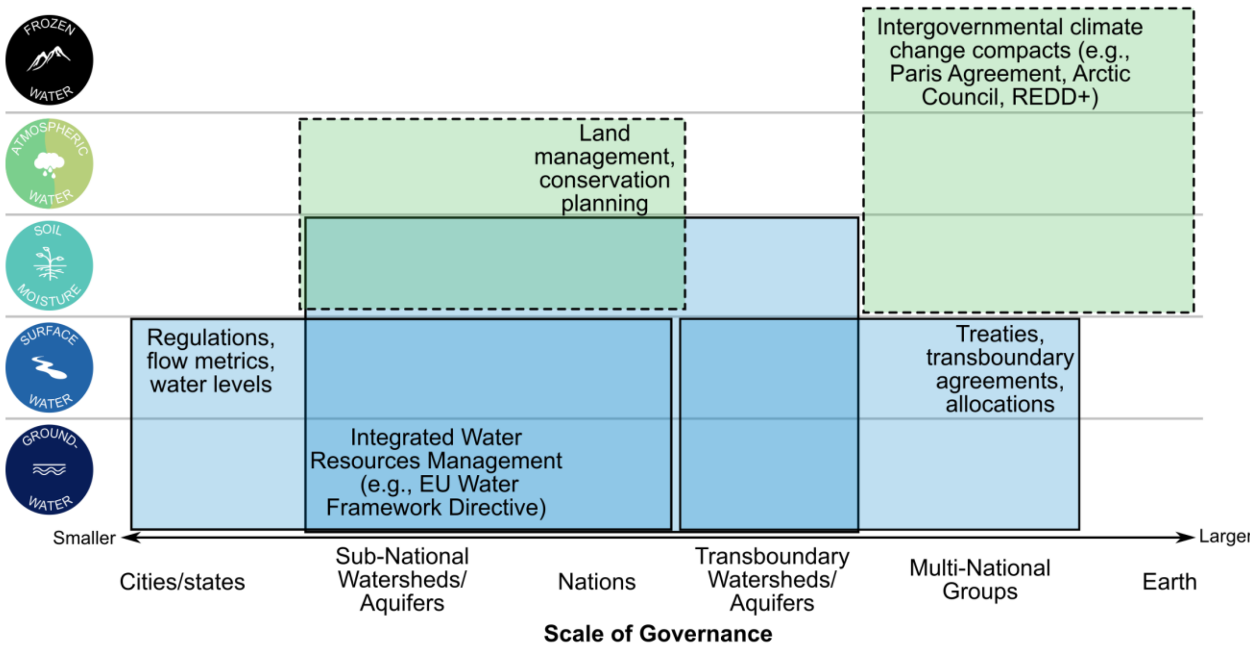

Figure 4. Examples of water management and governance approaches at different spatial scales targeting each store of water proposed for the water planetary boundary. Blue boxes are water resource management approaches and green dashed boxes are management approaches which are not designed specifically for water but likely to have a strong effect on that specific water store.

4.1 Watershed or aquifer management (single jurisdiction or transboundary)

At the watershed or aquifer scale, existing management approaches often identify critical threshold(s) of streamflow, aquifer or reservoir water levels, or some other metric describing stores or fluxes of water. When watersheds or aquifers cross administrative boundaries, relevant metrics include water allocations to different stakeholders. These metrics often balance socio-economic and biophysical considerations - for instance, how much water is necessary to support irrigated agriculture in the watershed while preserving sufficient in-stream flows for aquatic ecosystems. Integrated water resources management (IWRM) is a watershed-focused water management framework, which is typically applied at the watershed scale. Several core principles underlying IWRM and the planetary boundaries overlap: both frameworks treat different stores of water as inherently interconnected, and explicitly include land surface processes in the scope of water management (Badham et al., 2019). Since IWRM is designed to be applied at the watershed scale, the water planetary boundary provides a complementary framework for considering water flows that are not "seen" in IWRM - atmospheric, subsurface, and biosphere flows which cross watershed boundaries (Srinivasan et al., 2017). There is growing acknowledgment that human activities can directly or indirectly influence the stocks and flows of water beyond the watershed or nation in which they occur, through pathways including: (i) use in the production of goods and services, which enter or exit the area, i.e. through virtual water trade (Dalin *et al* 2017, Marston *et al* 2015) or foreign direct investment; (ii) flow through the atmosphere, i.e. moisture recycling (Wang-Erlandsson *et al* 2018, Keys *et al* 2012, 2014, 2016), or subsurface, i.e. regional groundwater flow (Ameli et al., 2018; Krakauer et al., 2014; Maxwell & Condon, 2016; McKenzie & Voss, 2013); (iii) through physical infrastructure, i.e. interbasin water transfers (Garrick et al., 2019; McDonald et al., 2014),within the realm of traditional water management; and (iv) altered land-atmosphere-ocean interactions, i.e. local groundwater depletion leading to global sea level rise (Döll et al., 2014; Wada et al., 2010). In particular, the importance of atmospheric water flows highlighted by the planetary boundaries framework indicates a need for integrating existing (blue) water management with domains typically thought of as land or climate governance, for example via land use planning and thus managing green water fluxes (Figure 4; Keys et al., 2017).

One example of how existing watershed-scale water management approaches may be complemented by water planetary boundary framework is the European Water Framework Directive (WFD), a water management approach at the watershed scale, which aims to reach and maintain "good" ecological and chemical status, defined relative to natural conditions (Kallis & Butler, 2001). However, the WFD does not aim to establish or define any boundaries, nor does it situate this status relative to potential broader scale feedbacks with Earth System processes (Bishop et al., 2009). Thus, the water planetary boundary framework complements the WFD in two primary ways. First, the fair shares approach to downscaling the water planetary sub-boundaries provides a tool for assessing whether management actions in Europe are sufficient to maintain water stocks and flows and good ecological conditions from an Earth System perspective, especially through quantifying externalized environmental impacts via consumption-based methods. Second, the local safe operating space approach provides a tool that can be used to set locally relevant boundaries within the context of the WFD, which is particularly needed for heavily modified or artificial water features, with WFD status that contain significant subjectivity, and prioritize outcomes based on the local social-ecological system. As of 2015, 47% of the European waters had not reached good ecological status, so it can also be argued that the Directive has fallen short in delivering coherent and sustainable water management in Europe (Voulvoulis et al., 2017). In sum, the water planetary boundary framework provides opportunities to better contextualize the WFD at both local and Earth System scales.

4.2 Political jurisdictions (state/province, national, multi-national)

Political jurisdictions use a number of policies, regulations, and incentives to govern water. These instruments are created and applied at numerous and often overlapping spatial scales (Wardropper et al., 2015). States/provinces, cities, or other local jurisdictions may supplement national water-related policies at sub-national scales. Multiple nations can be bound together through political and trade agreements, including political units such as the European Union and African Union; trade agreements such as North American Agreement on Environmental Cooperation and the ASEAN Free Trade Area; and intergovernmental organizations such as the United Nations.

Chapron et al. (2017) argue that these "legal boundaries" need to be designed and enforced in ways that translate the biophysical planetary boundaries into effective delimiters of human activities, either to prevent transgression of planetary boundaries or to scale down the human pressures on boundaries that are already exceeded. At the scale of an individual political unit such as a nation, the planetary boundaries framework provides a basis for considering the effects on stocks, flows and processes of water external to the unit's borders (whether geographic or institutional), which activities within the unit may impact. Transboundary water management frameworks have been developed for some watersheds and aquifers that cross political boundaries (Earle, 2013; Eckstein, 2011; Puri & Aureli, 2005). However, these are unequally distributed globally and focus primarily on surface water watersheds and to a lesser degree aquifers (McCracken & Meyer, 2018). To our knowledge, no existing water management agreements address atmospheric water flows across watershed boundaries, i.e. continental moisture recycling (Keys et al., 2016, 2017; Zemp et al., 2014), through which land use change or human water use can alter precipitation remotely (Keune et al., 2018; Wang-Erlandsson et al., 2018; Zemp et al., 2017; Zipper et al., 2019a). These transboundary atmospheric water flows indicate a need to expand the scope of water management beyond watershed and national scale and beyond blue water to include green and frozen water (see Section 4.1).

Political jurisdictions are inherently limited in their ability to regulate outside their physical boundaries. Calculating fair shares of planetary boundaries provides important information and incentives for setting aspirational and also operational goals for water managers and other actors to motivate action that addresses sustainability targets beyond their local geographic context, such as downwind and transboundary effects on water systems (Keys et al., 2018; Munia et al., 2016). The planetary boundary framework provides a tool, which can consistently be applied in multiple locations to estimate the relative contribution to a defined planetary boundary aligned with local boundaries.

One example of how the water planetary boundary may contribute to expand water management beyond watershed and national scale is provided by Häyhä et al. (2018). Taking a fair shares approach to downscaling, Häyhä et al. find that a consumption-based approach to water use (e.g., water footprinting) is essential to accurately calculate the European Union's total impact on water systems, because >40% of water use caused by EU consumption of goods and services takes place outside its borders, mainly through agricultural imports. By systematically applying the same method across all countries in the EU, the authors are able to provide a consistent framework for inter-regional comparisons. Additionally, Häyhä et al. conclude that the primary benefit of the planetary boundary framework relative to existing management approaches is the focus on interconnections between the water planetary boundary and other Earth System processes such as land system change and biogeochemical flows. While Häyhä et al. evaluated countries relative to the previously defined consumptive blue water use boundary (Rockström et al., 2009; Steffen et al., 2015), we expect that applying their same methods to the other suggested planetary boundaries (Table 1) would provide additional useful management context to compare among nations and regions and guide national-level water and land sustainability policy.

4.3 Commercial organizations (corporations, industries, financial institutions)

The water planetary boundary can also be used to guide decision-making of commercial organizations. It may benefit a private sector stakeholder by providing a basis for traceable metrics for demonstrating a commitment to global sustainability, and also scoping for shifts in risk exposure along the value chain. Since the UN 2030 Agenda and Paris Agreement explicitly include the private sector as actors, there is a growing demand for the development of science-based sustainability targets for commercial organizations, which consider negative impacts on environmental and hydrological resources (and societal spillover effects) across scales, from local to global. Clift et al. (2017) discuss the challenges and opportunities for businesses to use the planetary boundaries in their decision-making strategies. In particular, they note that the planetary boundary framework may provide a consistent approach to compare performance among different regions or companies using the fair shares approach outlined above (Table 3).

Effective use of the planetary boundaries can inform business decision-making by improving the understanding of the interdependence between economic activity and global sustainability. As long as full lifecycle impacts on water resources are accounted for, as described in Section 2, a corporation's fair share of the water planetary boundary could provide a globally consistent way to assess the water sustainability of a product or company, similar to a 'fair trade' or 'ocean-wise' product branding. Additionally, corporations can use the water planetary boundary framework to identify risks to water along their global supply chain (CISL, 2019). Recent work has shown that a relatively small number of transnational corporations, deemed 'keystone actors' as an analogy to the ecological concept of keystone species, have a disproportionate influence over Earth System function including marine ecosystems (Österblom et al., 2015), deforestation in boreal forests and the Amazon (Galaz et al., 2018) and more (Folke et al., 2019). Identifying and working with keystone actors in different local contexts could provide one mechanism to effectively manage water resources; such science-business partnerships are currently emerging for global fisheries management (Österblom et al., 2017). A reframing of management education may also be needed to better situate Earth System science within business education programs (Edwards et al., 2018)

Several companies are exploring ways to implement the planetary boundary framework. Butz et al. (2018) described an approach for translating planetary boundaries into 'economic intensities' to inform investment decisions. To account for effective water availability, they included toxic emissions to water and groundwater into their calculation. L'Oréal, the multinational beauty company also include measures of freshwater ecotoxicity as well as water resource depletion (Vargas-Gonzalez et al., 2019). Houdini, the outdoor clothing company, now includes a planetary boundaries assessment in its sustainability reporting (Haeggman et al., 2018). Alpro, the plant-based foods company, has piloted the use of the planetary boundaries framework as a basis for setting science-based targets for nature (Gladek et al., 2019), focused on translating corporate activities into environmental impacts. They propose accounting for both blue and green water use at the basin scale, similar to the context-based approach to target setting for water (Gillespy et al., 2017). The Kering fashion company has partnered with the University of Cambridge Institute for Sustainability Leadership to identify how businesses can best use the planetary boundary framework for assessing corporate sustainability (CISL, 2019). This report highlights the differences between 'downscaling' (i.e., fair shares) and 'upscaling' (i.e., local safe operating space approaches). CISL suggests that businesses should explore the opportunities of using the local safe operating space approach to guide corporate practices. Rather than trying to assess what is left to exploit, as might happen by comparing conditions to the global safe operating space under the fair shares approach, the focus should shift to actions needed to restore local environmental functioning in affected areas which would be identified using the local safe operating space approach. This is particularly important for globally heterogeneous boundaries like water because it considers hydrological impacts along the whole value chain, beyond the immediate local context.

Box 1. Local-global connections in the Cienaga Grande de Santa Marta Wetland Complex, Colombia

To demonstrate how the water planetary boundary framework may complement existing water management approaches, we present a case study of the Cienaga Grande de Santa Marta wetland complex in Colombia. The Cienaga wetlands are among the most productive coastal wetlands in the world (Cloern & Jassby, 2008) and a listed Ramsar Site (Ramsar.org, 2019). The mangrove-dominated system is highly susceptible to changes in salinity (Figure 5; Cardona & Botero, 1998; Elster et al., 1999), which is driven by the balance of freshwater inputs from precipitation and rivers, saltwater inputs from the ocean, and concentration of salinity via evapotranspiration within the wetland. The natural state of exchange between the rivers, ocean, and lagoon has been disrupted by human activity. Road construction in the 1950s cut off most surface water and groundwater exchange between the ocean and the wetland. In the 1970s and 1980s road and berm construction along the Magdalena River decreased freshwater inflows – these led to an increase in water salinity. Concurrently, irrigation and changes in land cover upstream led to a decrease in freshwater inputs and an increase in sediment loading to the wetland (Jaramillo et al., 2018a, 2018b; Perdomo et al., 1998; Rodríguez-Rodríguez, 2015). Beginning in the 1990s, the Colombian government developed a long-term environmental management plan for the Cienaga wetlands (Botero & Salzwedel, 1999; Vilardy et al., 2011), focused on restoring hydrological and ecological conditions by mangrove reforestation and dredging to increase freshwater inflows (Figure 5).

Mangrove cover has increased since the mid-1990s (Jaramillo et al., 2018a), but recovery is slower than expected (Röderstein et al., 2014).

The planetary boundaries framework helps identify multiple feedback mechanisms occurring at nested spatial scales which define the local safe operating space of the Cienaga wetlands (Figure 5). The primary goal of local management in the Cienaga wetlands is protecting the mangrove ecosystem. For the local safe operating space approach, *biosphere integrity* (response variable) depends on keeping *water salinity* (control variable) within a narrow optimal range (Figure 5, top row). Three hydrological mechanisms occurring at three different spatial scales influence salinity and thereby bound the local safe operating space: At the local scale, freshwater inflows to the wetlands are influenced by upstream blue water withdrawals for intensive agriculture, primarily banana plantations (Botero & Salzwedel, 1999; Vilardy et al., 2011). At the regional scale, the amount of incoming precipitation to the Cienaga wetland is influenced by ocean-atmosphere oscillatory cycles such as ENSO (Blanco et al., 2006; Hoyos et al., 2019; Jaramillo et al., 2018a; Restrepo et al., 2014) and also by terrestrial moisture recycling via evapotranspiration from the wetland's precipitationshed which has areas of high deforestation, including the Magdalena River Basin (Keys et al., 2016; Wang-Erlandsson et al., 2018; Zemp et al., 2014). At the global scale, sea level rise linked to ice-sheet melt and climate change increases ocean-wetland exchange. However, attention to the global scale alone could lead to a perverse incentive to allow increases in sea levels to improve wetland biosphere integrity, since sea salinity (~35 ppm) is lower than the current hypersaline conditions causing mangrove mortality (>100 ppm). These hydrological processes and likely boundary values are additionally modified and affected by ongoing environmental change in the Cienega wetlands, for instance upstream erosion and sedimentation associated with land use change reducing the hydrological connectivity between the river and the wetland and would therefore exacerbate the negative impacts of reduced flows caused by upstream blue water use (Botero & Salzwedel, 1999; Jaramillo et al., 2018b).

Applying the fair shares approach would apportion the water planetary sub-boundaries to the Cienaga wetlands. Using the sub-boundaries tentatively proposed by Gleeson et al. (2019a, 2019b) we apply the harmonization approach proposed in Section 3. We see a mixture of relationships between the local safe operating space and fair shares approaches. The surface water and groundwater sub-boundaries have different control variables. For the fair shares approach, the control variables primarily focus on in-stream conditions (environmental flows and low flow thresholds), while in the local safe operating space approach the control variable is concerned with net inflows into the wetland lagoon which are a function of blue water use. The soil moisture sub-boundary is only relevant in the fair shares approach because local net primary productivity is not strongly dependent on soil moisture since the mangrove wetlands are frequently inundated. The atmospheric water sub-boundaries also have different control variables in the two approaches: the fair shares approach uses changes in evaporation and precipitation change as control variables, and the local safe operating space approach uses deforestation in the precipitationshed of the contributing watershed. Finally, the frozen water sub-boundary has the same control variable (global ice volume) for both the fair shares and local safe operating space approaches, but the local safe operating space creates a perverse incentive for rising sea levels due to the historic construction of a coastal road. This mismatch indicates that the local safe operating space approach for frozen water is inconsistent with global water sustainability (Figure 3), and thus only the fair shares approach would be used for defining the safe operating space for frozen water in the Cienaga.

Combined, this analysis reveals several insights unaccounted for in current management efforts. First, the local safe operating space approach in particular can be integrated with as a tool for setting both limits to modification and targets for restoration of the local water system. Second, all aspects of the water cycle are important to the restoration of the Cienaga wetlands, though management (in the Cienaga and elsewhere; Figure 4) focuses primarily on surface water and, to a lesser degree, groundwater (Vilardy et al., 2011). Third, accounting for atmospheric water and frozen water requires a broad and cross-scale perspective which addresses for drivers and risks at the local, regional, and global scales (Keys et al., 2019). In summary, the water planetary boundary framework discussed here provides additional useful insight into the Earth System processes sustaining local ecosystems, and identifies actions at multiple spatial scales from local to global which can help sustain the Cienaga wetlands. These nested spatial scales of Earth System processes and feedbacks among management and other factors indicates that collaborative, multi-scale governance approaches will be necessary to halt or reverse the degradation of the Ciénaga wetlands (Biermann et al., 2012; Keys et al., 2017; Konar et al., 2016).

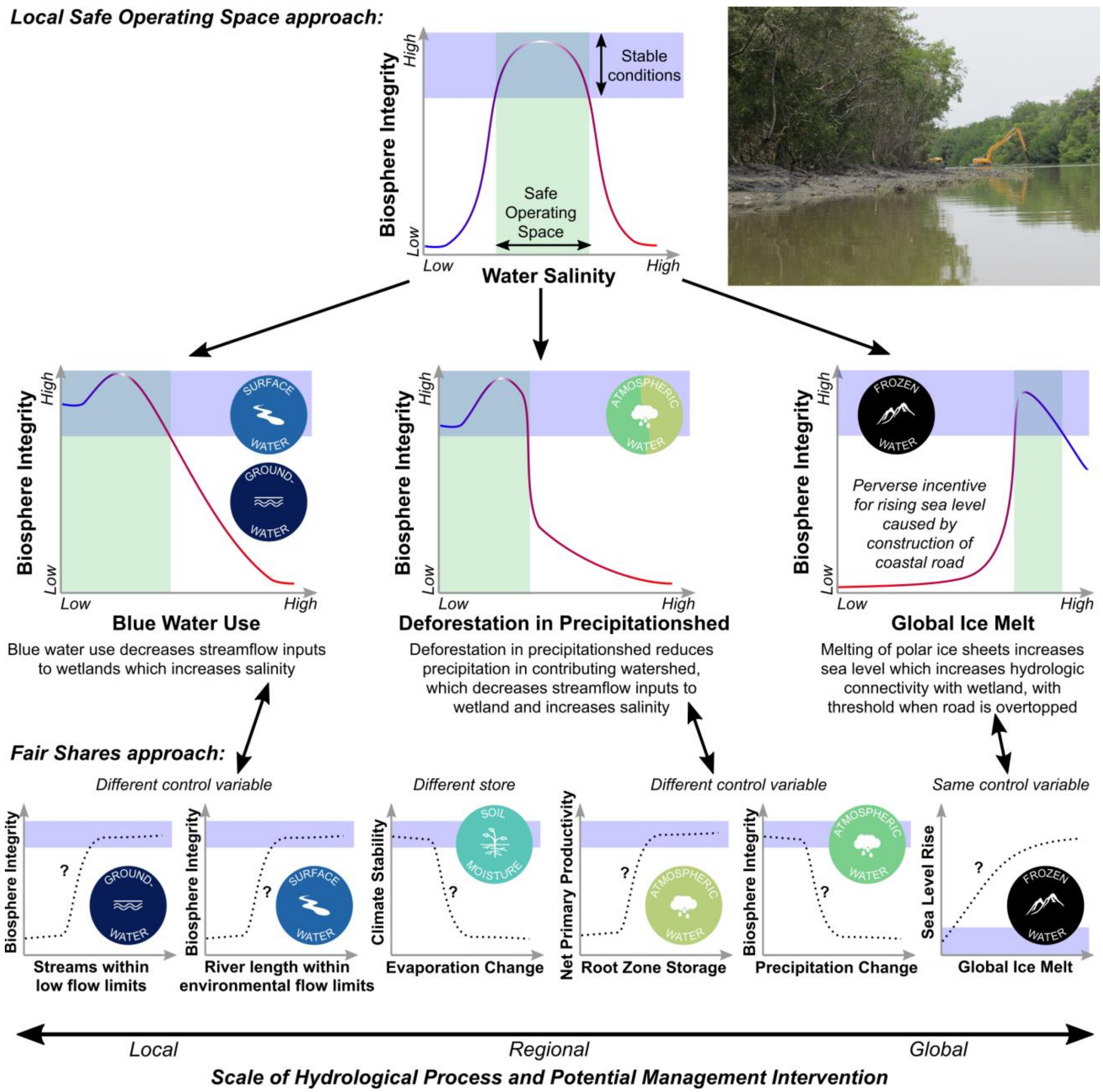

Figure 5. Example definition of local safe operating space for Cienaga wetlands including underlying Earth System processes at local, regional, and global scales identified using the planetary boundaries framework (top section) and the suggested control and response variables for the fair shares approach (bottom section) from Gleeson et al. (2019). The lines on the local safe operating space plots show hypothesized relationships based on feedbacks described below plots, and the lines on the fair shares plots are placeholders since global relationships necessarily for downscaling are not yet known. Inset photo by INVEMAR shows dredging of channels to increase freshwater inflows.

5. Further development of the water planetary boundary forward to complement current water management and governance approaches

While the planetary boundaries framework is recognised to have value in framing policy integration and supporting policy coherence - both across scales and across sectors, through different tiers of government - in practice, the studies we cite have generally remained as points for science-policy discussion rather than actual policy shifts. Here, we highlight three important aspects and research priorities that will enable better integration of planetary boundaries framework with existing water management and governance approaches.

First, the planetary boundaries framework can be regarded as a simple snapshot of a complex adaptive system. To integrate the planetary boundary framework with water management and governance, it is essential to consider not just the current value of the water sub-boundaries, but also their temporal dynamics and the current values, trajectories and potential systemic changes of the other boundaries, over the course of a policy-relevant timeframe. In addition, changes in planetary boundaries are likely to have knock-on effects on socio-economic dynamics, with potential feedbacks influencing the water sub-boundaries (Crépin et al., 2017). Each of the planetary boundaries is defined in terms of a notional Holocene-like state, which means that the control variables reflect the predominant interconnections and feedbacks of the Holocene Earth system - but these properties are changing in the Anthropocene (Waters et al., 2018), in particular because socio-economic feedbacks play an increasing role in the trajectory of the Earth system. For example, the transgression of the land system change and climate change planetary boundaries (Rockström et al., 2009; Steffen et al., 2015) are having consequences for the water cycle and its role in biophysical feedbacks, and actions to remain within those boundaries may help or hinder our ability to remain within the water planetary sub-boundaries (Heck et al., 2018b, 2018a; Stenzel et al., 2019). Policies based on water planetary boundary quantification should investigate not just the current status of a control variable, but also its trajectory and relationship to the temporal dynamics of other ecological and socio-economic components (Dearing et al., 2014). Since different hydrological processes act on dramatically different timescales (residence times for atmospheric water and groundwater differ by orders of magnitude; Oki & Kanae, 2006), adaptive water management approaches are needed that consider the time taken for a store of water to change relative to its current value and trajectory. Such adaptive approaches are key to sustainable water management (Gleeson et al., 2012b; Pahl-Wostl, 2007, 2008; Rohde et al., 2017).

Second, accounting for scientific uncertainty is a longstanding challenge for water management (Badham et al., 2019; Merz et al., 2015; Poff et al., 2016; Varela-Ortega et al., 2011; Wei et al., 2011). Given the complexities inherent in Earth System dynamics, there are numerous aleatoric and epistemic uncertainties embedded in the planetary boundaries framework which will need to be estimated and communicated to policymakers and others (Westerberg et al., 2017): uncertainty regarding the complex and nonlinear feedbacks in the Earth System (Steffen et al., 2018); uncertainty regarding the relationship between the control and response variables at both local and global scales; uncertainty inherent in both observational data and models used to quantify the current value of the control variable (Long et al., 2014; Sperna Weiland et al., 2015); uncertainty in the approaches for aggregating/disaggregating control variables and allocating the safe operating space globally (Mace et al., 2014); uncertainty in the harmonization process of the two approaches here discussed; etc. These uncertainties will most directly manifest in the definition of stable and unstable conditions for the response variable and integrating uncertainty into water management and governance, particularly aleatoric uncertainty which is inherently unpredictable (Poff et al., 2016). The precautionary principle suggests that, as uncertainty increases, so should the setback from the estimated threshold value, particularly given the large impacts of crossing these thresholds (Crépin & Folke, 2015; Margolis & Nævdal, 2008) and the presence of substantial time-lags (Crépin & Nævdal, 2019). Integrating the planetary boundaries into management frameworks will drive the creation and adoption of new data analytics and modelling tools that can better handle the complex behaviour of water in the Earth system, where it plays multiple physical, ecological and biogeochemical roles (Chang et al., 2018; Fan et al., 2019; Milly et al., 2014; Sippel et al., 2015).

Third, the scientific community needs to closely work with policy and decision makers in order to transparently identify relevant options that can meet existing local water management constraints while satisfying the Earth System sustainability defined by the water planetary boundary, and indicate how performance on a harmonized approach will be evaluated. This will require international commitment to transdisciplinary fundamental and solutions-oriented research, for example through existing science-to-policy approaches and boundary organizations such as Future Earth (Suni et al., 2016). As mentioned above, the water planetary boundary is just one of a set of nine boundaries with strong interrelationships. As scientific understanding increases about these interactions as well as about other changes in interrelated aspects of the Earth System, care needs to be taken to ensure that this shifting information baseline informs adaptive policy making rather than confounding it (Galaz et al., 2012a). If we adopt the mindset that the planetary boundaries are guardrails defining a ‘corridor’ which can be navigated through multiple socio-political pathways (Biermann, 2012; Qiu et al., 2018a), changes to other planetary boundaries (e.g., land system change) may alter the effective size and shape of the hydrological corridor bounded by the water sub-boundaries due to feedbacks between the water cycle and other components of the Earth System. This further highlights the need for iterative approaches such as adaptive management which provide the opportunity to regularly update management strategies and targets. In addition to its benefits, the planetary boundaries perspective may highlight new governance needs at both local and global scales (Biermann, 2012; Galaz et al., 2012b, 2012a), for instance fundamental incompatibilities between existing economic and environmental treaties (Biermann et al., 2012). But many of the integrated assessment models currently used for resource use assessments are essentially “black box” tools, where assumptions about human behaviour, social structures, and economic priorities are invisible to the user. From an evaluation perspective, as more societal actors become engaged in water management, care needs to be taken to avoid ‘greenwashing’ - creating the perception of water-friendly practices without having tangible impacts on the control variable of interest. Here, the harmonisation of fair shares and local safe operating space approaches can help avoid greenwashing, by providing ways to evaluate local management based on quantified changes in the value of a control variable, rather than practices intended or believed to have a positive benefit.

6. Conclusions

The planetary boundaries are a useful framework for defining the global safe operating space for humanity. However, the use of the planetary boundary for water management and governance at sub-global scales encounters major challenges in reconciling the global-scale definition of the planetary boundary with the smaller scales in which water decisions are made. Previous work to translate the water planetary boundary to local contexts has primarily adopted either a fair shares approach, which calculates the maximum allowable local contribution to the global planetary boundary and quantifies the global responsibility (contribution) of the local water use; or a local safe operating space approach, which uses the principles of the planetary boundary framework to define locally-relevant boundaries.

We present a harmonized approach to local use of the water planetary boundary which combines the advantages of the fair shares approach (global responsibility) and the local safe operating space approach (local relevance). This approach, based on the precautionary principle, can be used in both socially-defined contexts (cities, nations, intergovernmental or companies or industries) and physicallydefined contexts (watersheds, aquifers, continents). Using these harmonized water sub-boundaries will ensure that actions in a local context are contributing to water sustainability at all scales from local to global. Integrating the water planetary boundary with existing water management and governance approaches provides a framework to incorporate effects on water systems beyond the local, national, or watershed context; integrates socio-economic and ethical considerations with biophysical constraints; and provides a consistent approach for inter-regional comparisons. Furthermore, the water planetary boundary further highlights the need for adaptive water management approaches which can respond to complex, nonlinear changes in Earth System processes.

Acknowledgments

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Tables

Table 1. Proposed water planetary sub-boundaries from Gleeson et al. (2019a, 2019b) which correspond to water stores and functions. Note that control variables are not defined.

Water Store	Core function of this water store in Earth System	Possible response variable(s)	Possible control variable(s)	Cross-scale interaction not considered in traditional water management approaches
Atmospheric water	Hydroclimatic regulation	Climate pattern stability or land-atmosphere coupling	Land area with evaporation change	Changes in precipitation due to upwind changes in land use or irrigation (Keys et al., 2017)
	Hydroecological regulation	Terrestrial biosphere integrity	Land area with precipitation change	
Soil moisture	Hydroclimatic regulation	Carbon uptake or net primary productivity	Global root zone storage capacity	Trade-offs between global CO_2 budget and local water availability (Heck et al., 2018b)
Surface water	Hydroecological regulation	Aquatic biosphere integrity	Watersheds or total river length within environmental flow limits	Importance of local aquatic systems to global biodiversity pool (Mace et al., 2014)
Groundwater	Storage	Terrestrial or aquatic biosphere integrity	Watersheds with sufficient low flows	Groundwater coupling with global climate system (Cuthbert et al., 2019)
Frozen water	Storage	Sea level rise	Volume of ice melt	Local responsibility for global sea level rise (Hardy & Nuse, 2016) and knock-on impacts on other planetary boundaries (Crépin et al., 2017)

Table 2. Previous use of the planetary boundaries in local contexts. Shaded rows indicate studies which did not define a water boundary.

Study	Context	Approach (all planetary boundaries)	Details related to water planetary boundary
Nykvist et al. (2013)	National (Sweden)	Fair shares: compare Sweden's performance to Rockström et al. (2009) boundaries using per-capita downscaling	*Control variable:* Consumptive blue water use *Response variable:* Not stated *Details:* Argue that fair shares approach not relevant for water since it does not account for regional variation in water availability
Cole et al. (2014)	National (South Africa)	Local safe operating space: develop local indicators and boundaries based on primary environmental concerns in South Africa	*Control variable:* Consumptive blue water use *Response variable:* Biosphere integrity (implicitly by defining boundary based on local environmental flow needs) *Details:* Quantified surface water availability after accounting for environmental flow needs, added estimated safe groundwater yield
Dearing et al. (2014)	Sub-national (two regions within China)	Local safe operating space: develop local control and response variables based on time-series data for primary environmental concerns	Water boundary was not defined - primary regional issues are water quality, air quality, and sedimentation.
Hoff et al. (2014)	National (all nations within European Union)	Fair shares: compare national performance to Rockström et al. (2009) boundaries using per-capita downscaling	*Control variable:* Consumptive blue water use *Response variable:* Not stated *Details:* Acknowledges limited utility of per capita downscaling, suggest future work should use context-specific factors such as environmental flows and also green water
Dao et al. (2015)	National (Switzerland)	Fair shares: compare national performance to Rockström et al. (2009) boundaries using per-capita downscaling with consideration of past and future generations	Water boundary was not defined - authors argue that only regional limits exist and global threshold not relevant.
Kahiluoto et al. (2015)	National (Sweden and Ethiopia)	Local safe operating space: estimated local biochemical flows boundary based on historical data Fair shares: per-capita downscaling of Carpenter & Bennett (2011) and Steffen et al. (2015) boundaries	Water boundary was not studied.

Sandin et al. (2015)	Industry (clothing in Sweden)	Fair shares: compare industry performance to Rockström et al. (2009) boundary using four ethical approaches	*Control variable:* Consumptive blue water use *Response variable:* Not stated *Details:* Compared four different ethical approaches to apportioning impacts. Note that framework could be adopted for regional, context-specific analysis.
Fanning & O'Neill (2016)	National (Canada and Spain) and sub-national (Nova Scotia and Andalusia)	Local safe operating space: calculate carbon, nutrient, water, and land footprint relative to local thresholds	*Control variable:* Consumptive blue water use *Response variable:* Biosphere integrity, implicitly by defining boundary based on local environmental flow needs following Steffen et al. (2015). *Details:* Use threshold of blue water consumption exceeding blue water availability for >3 months annually
Teah et al. (2016)	Sub-national (Middle reaches of Heihe River, China)	Local safe operating space: develop local indicators and boundaries based on primary environmental concerns in South Africa	*Control variable:* Consumptive blue water use *Response variable:* Not stated *Details:* Separately calculated low-risk and high-risk boundaries.
Brejnrod et al. (2017)	Individual building (comparison of two types of houses)	Fair shares: calculate performance of a single building relative to the per-capita carrying capacity	*Control variable:* Consumptive blue water use *Response variable:* Not stated *Details:* Primary water savings could be obtained by reducing living area per person.
Wolff et al. (2017)	Company (mass-market retailer)	Fair shares: Assess only one step in supply chain (agricultural production for food portfolio); full assessment of entire supply chain not feasible.	Water boundary was not defined - case study focused on biodiversity only.
Häyhä et al. (2018)	National (all nations within European Union)	Fair shares: compare per-capita and consumption-based downscaling of Rockström et al. (2009) boundaries	*Control variable:* Consumptive blue water use *Response variable:* Not stated *Details:* Suggest future work constrain freshwater use based on regional environmental flow limits
O'Neill et al. (2018)	National (all nations)	Fair shares: compare national performance to Rockström et al. (2009) boundaries using per-capita downscaling	*Control variable:* Consumptive blue water use *Response variable:* Not stated

			Details: Acknowledge limitations of per-capita downscaling
Ryberg et al. (2018)	Industry (laundry washing within European Union)	Fair shares: compare national performance to Rockström et al. (2009) boundaries using four downscaling approaches	*Control variable:* Consumptive blue water use *Response variable:* Not stated *Details:* Downscaling approaches based on economic indicators (consumption expenditure and gross value added). Choice of downscaling approach significantly affected results.

Table 3. Methods by which the water planetary boundary complements typical water management approaches in different contexts.

Context	Typical Management Approaches or Metrics	Value added by fair shares approach	Value added by local safe operating space approach
Watershed or aquifer management (single jurisdiction or transboundary)	Flow metrics, groundwater levels, allocations, IWRM	● Integrating water with other Earth System functions, socio-economic, and ethical considerations ● Account for impacts outside the local context (global citizenship).	● Integrating water with other Earth System functions, socio-economic, and ethical considerations ● Considering water fluxes beyond traditional water system boundaries
Political jurisdiction (state, national, multi-national)	Water policy and regulations, trade agreements, treaties	● Integrating water with other Earth System functions, socio-economic, and ethical considerations ● Account for impacts outside the local context (global citizenship). ● Provides consistency for comparing different countries or members	● Integrating water with other Earth System functions, socio-economic, and ethical considerations ● Considering water fluxes beyond jurisdiction boundaries
Commercial organization (corporation, industry)	Life cycle analysis, industry standards, water footprinting	● Demonstrate commitment to global sustainability ● Provides consistency for comparing different companies or regions	● Evaluate resilience of supply chain

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