Values-Based Scenarios of Water Security:

Rights to Water, Rights of Waters, and Commercial Water Rights

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Abstract

While a wide body of scholarly research recognizes multiple kinds of values for water, water security assessments typically employ just some of them. Here we integrate value scenarios into a planetary water security model to incorporate multiple water-related social values and illustrate tradeoffs among them. Specifically, we incorporate cultural values for environmental flows needed to sustain ecosystem function ("rights of waters"), the water requirements of a human right to food ("rights to water"), and the economic value of water to commercial enterprise ("commercial water rights"). Pairing quantitative hydrological modeling with qualitative systems of valuing, we suggest how to depict the available water for realizing various combinations of the values underlying those rights. We account for population growth and dietary choices associated with different socio-economic pathways. This pluralist approach incorporates multiple kinds of values into a water security framework, to better recognize and work with diversity in cultural valuation of water.

Introduction

Water security emerged in the second half of the 20th century as an environmental governance framework encouraging sustainable management of a scarce resource (Schmidt 2017). Its basic objective was to manage conflict over competing values, centrally between efficient resource distribution and support of human needs (Keeler et al. 2020). By the time of the 2000 World Water Forum in the Hague, water security had become the key idea for negotiating normative debates in global water governance (Cook and Bakker 2012). Many of those debates centered on what values should be included in water security assessments and how to compare across them to find the best way to distribute a limited resource. The concept of water security initially continued the prevailing utilitarian approach to comparing values through cost-benefit analysis (Conca 2006, Feldman 2007). That approach had the advantage of permitting quantitative modeling, but the disadvantage of either excluding other socially important ways of valuing water or reducing them into the value of efficiency.

The water security framework was reformulated in the early 21st century, shifting from efficiency to sufficiency and from sustainable development to resilience, in order to reflect the scale of anthropogenic influence over hydrological systems (Schmidt 2017). Moving from resource limits to the "safe operating space" for freshwater appropriations in relation to other planetary boundaries (Rockström et al. 2009, 2014) suggested rethinking water security in relation to the functioning of planetary systems (Steffen et al. 2015). Meanwhile, in 2010 the UN General Assembly recognized a human right to drinking water and sanitation (U.N. 2010), in addition to the right to water for food production implicit in the human right to food (U.N. 1948). The objective for water security was thus reformulated around a central tension: develop sufficient water capacity to realize human rights to water and food while redirecting overall appropriation to protect planetary systems.

Yet while planetary models of water security have in turn sought to address the uneven, complex effects of human actions across multiple scales (Rockström et al. 2012, Gleeson et al. 2020), they still represent a narrow range of values. Water governance scholars and practitioners increasingly recognize that they must take account of more diverse ways of valuing water, which may include not only distributive fairness and aggregate prosperity but also cultural and religious conceptualizations of water (Kallhoff 2014, Zenner 2019). From 2016-18, the UN High-Level Panel on Water convened a series of global workshops through its "valuing water" initiative, which sought to reconcile the human right to water with the economic value of water uses, while also recognizing other social and cultural values (see Garrick et al. 2017). Those other values, however, were ultimately reduced to a tradeoff between the human right to water and highest economic value (Schmidt 2020).

In their review, Zeitoun et al. (2016) argue that researchers tend to accommodate the challenge of multiple water values by taking one of two approaches: either reducing risks and complexity into a singular frame of reference or integrating plural values by localizing the context. Schmidt (2017) argues that both approaches nonetheless retain the premise of "normal water" – a conception of water as a resource for supporting an historically narrow range of social organization. Communities that conceptualize and value water differently expose the contingency and limits of normal water (e.g., Young and Loomis 2014, Cano Pecharroman 2018, Opperman et al. 2020). Water values are as diverse and wide-ranging as cultural imaginations.

Tension between diversity of values and the need for comparison thus represents a critical challenge for water security. "Alert to the critique of reductionism," Doeffinger et al. (2020) have developed a "dashboard" comprised of 52 variables reflecting a "broad and holistic understanding of water security" (p. 826). Their tool addresses the challenge between diversity and commensurability by incorporating many contextual variables into a composite representation that permits relatively rapid appraisals and comparison across context. However, they explicitly exclude "historical and cultural context" (Doeffinger et al. 2020, 832). While recognizing it as a major category for understanding how a particular water system functions, they deem the related variables too difficult to include. Their dashboard for the Indus River basin, birthplace of three world religions, thus does not have a way to recognize values arising from the long history of regarding the Indus River as sacred. Doeffinger et al. regret the shortcoming and name incorporation of cultural values as a key point for methodological advancement.

Meanwhile, that methodological challenge particularly disadvantages Indigenous communities. Indigenous representatives in water governance arenas regularly observe that the UN Declaration on the Rights of Indigenous Peoples (UNDRIP) acknowledges cultural values of water, including the possibility of sacred and intrinsic values for water. As Emanuel and Wilkins (2020) explain, "UNDRIP affirms that Indigenous peoples have rights to maintain spiritual relationships with waters of their territories (Article 25) and to give free and informed consent prior to the development or exploitation of their water and other resources (Article 32)." While Indigenous modes of valuing water are typically excluded from water governance conceptual frameworks, in many specific arenas of water governance Indigenous peoples invoke UNDRIP "to defend their treaty rights, exercise their sovereignty, preserve their cultures, or protect their interests in other ways" (Emanuel and Wilkins, 2020). As a matter of procedural justice then, water security tools need to incorporate a broader range of cultural values.

Is it possible to account for broader diversity in water values while permitting comparison across their hydrological entailments? This article takes a step toward a more pluralist water security model – that is, a model more capable of incorporating different kinds of values without reducing them to a single norm. First, we describe "rights of waters" as proxy for a range of cultural valuation typically excluded from water security assessments. Drawing from literature on relational and intrinsic values, with special attention to Indigenous sources, we discuss ways of connecting those values to quantitative data on environmental flows, which are here expressed as minimum instream requirements to sustain ecosystem function (e.g., Wohl, 2020; p. 218). We then illustrate how rights of waters could interact with human rights to water and to commercial water rights, which function as proxies for conflicting logics of valuation that underly competing claims to water. Working with data on hydrological entailments of each proxy, we develop a model of planetary water security that enables comparison of the material, volumetric requirements of pursuing different values.

The result is not an optimizing equation that would solve for water security by reducing conflicting water values into a single norm. Our purpose is primarily heuristic, sketching a possible approach to diversifying water governance. We do, however, illustrate biophysical boundaries to realizing various combinations of values. By integrating hydrological requirements for the three proxies, and showing variables in the social determination of each, we illustrate how much water is available for pursuing different value combinations. Again, the point to this exercise is not to lay out one pathway for ensuring water security. Rather, by framing water security as a hydrological relation among social values we rather aim to diversify conceptions of water security while also stimulating critical deliberation over those values.

Integrating Rights of Waters

The concept of relational value originated in resource economics to express the idea that value does not reside wholly in objects nor wholly in subject preferences, but rather emerges from the interaction between subject and object (Brown 1984). Since then, relational values have been developed and applied in conservation biology and studies of ecosystem services (Himes and Muraca 2018; Chan et al. 2018). More recently, Anderson et al. (2019: p8) argued that "relational values are key to pluralistic environmental valuation" that incorporates environmental flows into effective water management. They extend relational values to water by also claiming that "relational thinking has gained the most traction in contexts where Indigenous peoples have a significant stake in a water management issue" (Anderson et al. 2019: p9).

In principle, water governance should be able to take seriously the many, longstanding assertions of Indigenous peoples that waterways have their own rights and responsibilities. However, modern forms of water governance often cannot recognize the relational values involved in Indigenous environmental governance (Sabatier 2005; Boelens et al. 2010, Emanuel and Wilkins 2020; Middleton, 2018). As Indigenous philosopher Kyle Whyte (2017) explains, when a people understands a waterway as a member of their political community, with responsibilities and duties of its own, their value for that relation is rendered illegible by mainstream processes of environmental governance. Indigenous values for water may not be appropriately explained on a spectrum running from human rights to economic usage rights (Hoover 2017; Wilson and Inkster 2018). What flow requirements are entailed by permitting water to perform its responsibilities? Answering would require interpreting water security through a wider set of social, legal, and hydrological relations.

Water security models typically neglect any notion of water as sacred, as a legal person, or as intrinsically valuable, despite the prevalence of those values in political communities and in established normative discourse. For example, while Indigenous people appeal to UNDRIP's recognition of their values, global water governance frameworks often focus on the UN Millennium Development Goals while ignoring the UNDRIP. Meanwhile, Indigenous conceptions of water have been influential in legal rulings, in which the rights of particular waters have been affirmed by courts in New Zealand, Columbia, Ecuador, and India (Cano Pecharroman 2018). One powerful example is the role of Māori values in recognizing legal personhood for the Whanganui River in 2017. That decision allows policy-makers to consider the river's inherent right to flow, transport sediment, and host life (Brierley et al. 2019, Salmond et al. 2019).

Excluding such values may be unjust in itself, by not recognizing forms of valuing water that are central to the identity of particular communities (Emanuel 2019). This deficiency particularly affects those Indigenous peoples who regard water as living, or a specific waterway as a cosmopolitical being with whom they share reciprocal relations (Whyte 2017). For that reason, *Mni wičoni* – the Lakota/Sioux phrase sometimes translated into English as "water is life" or "water is living," which rose to international prominence during the 2016 Standing Rock Sioux protests of the Dakota Access Pipeline – has become a political slogan that stands not only for protecting the Mni Sose waterway but also, more generally, for respecting Indigenous ways of relating to water (Estes 2019). Beyond Indigenous communities, reference to bodies of water as sacred or venerable appears across many cultures and traditions (O'Donell and Talbot-Jones, 2018).

Respect for how particular communities value particular waters is key to understanding water's role in sustaining human and non-human relations (Kallhoff 2014, Schmidt 2017). It is also central to understanding the co-evolution of people and landscapes – what Falkenmark and Folke (2002) term "hydrosolidarity" in their account of water, food, and biodiversity within emergent social-ecological systems. Moreover, recognizing relational values in water security can deepen understanding of predominate value systems by stimulating comparison. As Anderson et al. (2019: p15) observe, "granting legal personhood to rivers foregrounds reciprocal exchanges between people and rivers, emphasizing mutual responsibilities over narrow utilitarian definitions of human benefit from water." The relational perspective portrays the predominate conception of human benefit as but one historically contingent perspective among multiple possibilities.

Other ways of valuing waterways for their environmental flows – which may be proximate to relational values but are independently derived – include ecocentric positions in environmental ethics that arise from accounts of intrinsic value (Curry 2011, Rolston 2012, Washington et al. 2017, Crist 2019). Contrasting themselves with anthropocentric, instrumental perspectives that value "natural resources" only on the basis of their direct or indirect use to human beings (Daily et al. 2000, Brauman et al. 2007), these ecocentric approaches (de Perthuis and Jouvet 2015) value ecological relations also on the basis of intrinsic value. These philosophical positions have a long history in practical matters of water policy in the United States (Feldman 1991, Ingram 1986), and include proposals to recognize rights of nature in western legal traditions (Stone 1974, Chapron et al. 2019).

We use 'rights of waters' as a shorthand for ecocentric commitments included in accounts of relational values and intrinsic values of specific rivers, lakes, aquifers or other water-related geographic features or ecosystems. As a proxy, it is a rough representation, itself encompassing forms of valuing from quite different cultural sources, even while not fully representative of all water-related cultural values including Indigenous perspectives mentioned above. Nonetheless, we hold that "rights of waters" helps incorporate a fuller range of environmental, social, political, and legal water values into criteria for water security.

In our nonfoundationalist approach – that is, an approach that does not seek to integrate water security into one conception of values – the values bundled into "rights of waters" are not reduced into the utilitarian scheme of value that underpins commercial water rights nor into the normative scheme of value justifying the human right to water. Instead, our approach recognizes those major forms of valuing and incorporates "rights of waters" alongside them. Our aim is to illustrate the hydrological implications of different kinds of values. By modeling the rights of waters in relation to a human right to water and commercial water rights, we provide a way to conceptualize the effects of different value regimes on interpretations of water security.

We model three different environmental flow levels for protecting the rights of waters. There is debate within conservation ecology over how to determine minimal flow requirements for preserving the ecological function of rivers (Richter et al. 2012, Pastor et al. 2014, Ziegler 2017). Protecting rights of waters could conceivably entail different levels of protection from extractions. Such limits might, for instance, entail more or less strict limits on the withdrawal levels that already affect aquatic habitat in many of the world's rivers (Postel and Richter 2003, Wada et al. 2010, Jägermeyr et al. 2017, Rosa et al. 2018a). Some relational values may focus on a particular species or ecological function rather than the water body itself. Our use of environmental flows to represent those varied ways of relating to water is consistent with implementation of tribal water rights in U.S. water management, where rights based on subsistence fishing or other cultural practices have been recognized in terms of flow and habitat needs of relevant species (Confederated Tribes v. Walton 1981, United States v. Adair 1983). By modeling three environmental flow levels, our goal is not to exhaust all possible cultural valuation but to illustrate how various socially determined conceptions of rights of waters have different hydrological implications.

To what extent does recognizing rights of waters compete with human rights to water and commercial water rights? Human rights to water are much more extensive than direct consumption for drinking and sanitation. The UN Universal Declaration of Human Rights recognizes food as a human right (UN 1948) and food production relies on water use for irrigation, which will likely increase in the near future (Falkenmark and Rockstrom et al. 2004, Beltran-Peña et al. 2020). Thus, the right to food implies a human right to water for food production (e.g., D'Odorico et al. 2018, Hoekstra 2020). To be clear, while the UN has recently recognized also a right to water for drinking and sanitation (UN 2010), that constitutes only a fraction of what we include in the human right to water because human water consumption for food production is an order of magnitude greater than that for drinking and sanitation (Falkenmark and Rockstrom 2004). We consider this entire hydrological entailment with the proxy "right to water."

Crop production requires water consumption (i.e., water loss to the atmosphere by evapotranspiration) both in the form of rainwater (or "green water") in rainfed agriculture and in the form of irrigation, which uses water from rivers, lakes, or aquifers (or "blue water"). Indeed, the majority (90%) of human consumption of freshwater goes to irrigation, mostly for the purposes of food production. While only ~23% of croplands worldwide are irrigated, irrigated lands account for 40% of global crop production (Siebert and Doll 2010). Moreover, in order to keep pace with the increasing demand for food commodities without expanding the footprint of agriculture, humanity will likely have to introduce irrigation in currently rainfed agricultural areas (Falkenmark and Rockstrom 2004, Mueller et al. 2012). Yet many agricultural regions face hydrological constraints on the expansion of irrigation (Rosa et al. 2018a, 2020). Similarly, appropriation of water for commercial farming or for the transition from subsistence to large-scale agriculture, while arguably capable of enhancing global food supply (Herrero et al. 2017), displaces water from traditional systems of production and the associated cultural values for Indigenous groups and rural communities (de Schutter 2011, Metha et al. 2012, Dell'Angelo et al. 2018).

By taking a pluralist approach, we can better specify competition among the values variously represented by rights of waters and the human right to food, and in the relation of both to economic values of water for business uses. The example we develop here illustrates ways of allocating hydrological space among the different kinds of values, correlative to some widely held political commitments. Specifically, it works from basic commitments to justice and safety as conceptualized in planetary boundaries discourse (Rockstrom et al. 2009, Raworth 2012). Those boundaries represent contingent values; hypothetically, a model could illustrate different hydrological boundaries if it – for perverse example – suspended commitment to human rights.

In this paper, we use the term 'floor for justice' to mean the minimum amount of water needed to meet the human right to food, as calculated in the model. We use the term 'ceiling' to mean the maximum amount of water that humans can appropriate for their use under a specified 'sustainability' (i.e., environmental flow) scenario. Our work shows the minimum hydrological floor for justice in this particular conceptualization by calculating the water needed to meet the human right to food. It then investigates how that floor relates to the ceiling of safe human appropriation of water systems, as depicted by different conceptions of rights of waters.

The resulting domain between floor and ceiling yields one way to represent a "safe and just operating space for humanity" (Raworth 2012). Concepts of limits and boundaries can sometimes mislead political deliberation by concealing the values by which limits are interpreted (Kallis 2019). By adjusting the floor and ceiling according to different specifications of the underlying values we show the social construction of boundaries, depict the resulting hydrological space available for different uses under different value combinations, and open ways for communities to deliberate over the underlying tradeoffs.

One of the most important depictions has to do with equity, especially the actual range of inequality in consumption. The most recent assessment of the planetary boundary for freshwater by Gleeson et al. (2020) argues that an “equity-based allocation framework” is key to addressing social and environmental water challenges. Meanwhile equity may be pressured by vectors of change in hydrological systems (O’Neill et al. 2018; D’Odorico et al., 2019). If that span between a floor of justice and ceiling of safety narrows, then the range of available values-based scenarios within planetary boundaries also narrows, increasing pressure on water security deliberations.

We show how a model based on a floor of rights *to* water adjustable by varying criteria of equity and on a ceiling of rights *of* waters adjustable by varying criteria for environmental flows, could help societies deliberate over how much hydrologic space to make available for non-food business operations, to which we refer as “commercial water rights.” We treat these interests in water separately from agriculture because they may compete with food systems and with environmental flows. Moreover, important differences exist between water use in agriculture and other economic activities. Mining, power generation, and industrial processes generally consume a much smaller amount of water than irrigation. Yet they also attain much higher economic efficiencies in terms of revenue generated per unit volume of water consumption (D’Odorico et al. 2020). Economic value of water may then direct flows away from food production or ecological replenishment, thus putting pressure on values for equity and/or ecological integrity (e.g., Bonnafus et al. 2017, Rosa et al. 2018b).

Competition among human rights to water and commercial water rights varies according to a variety of contextual factors, including legal structures, property institutions, and mechanisms of allocation. For instance, in the few regions of the world where water markets exist (Endo et al. 2018) businesses typically displace agricultural needs in the use of water because of the lower revenues generated by agriculture and the ability of markets to allocate water to uses with higher direct economic return (Debaere and Li 2017). Water markets typically emerge in the presence of tradeable commercial water rights (Johansson et al. 2002). Yet even where property rights in water do not exist and water is perhaps treated as a public good or common pool resource (e.g., Ostrom 1990, Anisfeld 2010, Schmidt and Mitchell 2014), commercial uses may still attain preferential access to water allocation through mechanisms ranging from concessions and permits to water grabs (Mehta et al. 2012, Dell’Angelo et al. 2018). Sometimes market devices may be used to cap water withdrawals or to enable philanthropic water purchases for habitat restoration and environmental flows (Debaere et al. 2014, Richter 2016). Typically, however, market-based approaches to water security work with one kind of valuation for water, while also competing with human rights to water.

Values-Based Scenarios of Water Security

Our water security framework provides a way to diversify understandings of water security, which is analyzed by looking at the extent to which the global irrigation water consumption, *IWC,* is sufficient to meet the food needs of humanity, while ensuring local environmental flows and some availability for non-food economic uses. Without attempting to account for all water-related cultural and social valuing, this model expands quantitative understanding of water scenarios with a few qualitative parameters corresponding to values relatively well-established in normative ethics.

Variables for rights of waters must be evaluated at different scales from those for rights to water because, while environmental flows matter primarily for local ecological and cultural systems, food demand is global. Indeed, on average about 25% of the food consumed by humanity is supplied by international trade (D'Odorico et al. 2014). Many regions of the world are not self-sufficient because they exhibit an imbalance between their food needs and the local agricultural resources (Kinnunen et al. 2020, Beltran-Peña et al. 2020). Because the right to food has not yet been recognized as a right to *local* food and water resources, despite efforts from food sovereignty movements, we express food supply needs at the global scale, set in relation to local environmental flows expressed as rights of waters. In other words, food demand is global and globalized, while the environmental and cultural impacts of water consumption from food production are local. We assume perfect trade opportunities for food (i.e., every country has access through trade to global food production), while environmental flow needs are evaluated locally (at 50 km resolution, while accounting for water flows from the watershed upstream from every 50 km x 50 km location).

We may express this by saying that the rights of waters are protected if water consumption for irrigation (IWC_i) at a certain site, i, added to other local water uses for municipal and industrial needs (OU_i) does not exceed the difference between local annual surface and groundwater runoff, RO_i, and the local environmental flow requirements (EF_i) (see Box 1 for an explanation of the notation and other definitions):

$$IWC_i + OU_i \leq RO_i - EF_i \tag{1}$$

The actual maximum human appropriation of water for irrigation depends on crop distribution and the associated irrigation water requirements, IWR_i, calculated with a crop water model (see Methods). Crop distribution is highly sensitive to the availability and pricing of inputs, including water, as well as market demands and technological changes. Here we consider the global crop distribution determined for the year 2000 (see Methods). Even though changes in crop distribution can increase agricultural production and improve water use efficiency (Davis et al., 2017), we refer to the distribution reported for 2000 as a baseline scenario to evaluate the associated irrigation water requirements worldwide. Thus, based on equation (1), irrigation water consumption at site *i*, IWC_i, is equal to IWR_i if the water sustainability constraint (eq. 1) is met. If the entire *IWR* cannot be met sustainably, we first assume that there is no irrigation; in that case, $IWC_i=0$. We then consider also a "deficit irrigation" scenario whereby investments in irrigation infrastructure are made even when only a fraction (here taken equal to 70%) of irrigation water requirements can be met. This scenario corresponds to a 30% water deficit with respect to the irrigation water requirements. The sum of all the values of IWC_i in all the agricultural areas around the world gives an estimate of the maximum global limit to irrigation water consumption (or the "planetary boundary" for water in agriculture):

$$IWC_{max} = \sum_i (RO_i - EF_i - OU_i) \geq \sum_i IWC_i = IWC. \tag{2}$$

When performed on all cultivated land, this analysis expresses the global limit to irrigation water consumption in areas that are presently cultivated. In fact, the areas that do not contribute to this sum (eq. (2)) are either not cultivated, are cultivated but do not need to be irrigated, or need to be irrigated but do not have a sufficient amount of available water resources to (sustainably) meet the irrigation water demand. This framework was previously used to determine the limit to irrigation. Indeed, some regions are presently irrigated beyond the water sustainability limit expressed by (1). Likewise, the framework shows that there is also a limit to irrigation expansion in areas that are currently rainfed (Rosa et al. 2018a).

Box 1. Notation and definitions

Irrigation Water Consumption (IWC): The water volume (per unit time) abstracted for irrigation that is evapotranspired.

Irrigation Water Requirement (IWR): The amount of irrigation water consumption that is needed in order to avoid crop water stress.

Other uses (OU): The volume (per unit time) of abstracted water for domestic and industrial needs that is evapotranspired.

Runoff (RO): the sum of land surface and groundwater flows.

Environmental Flow Requirements (EF): Minimum instream requirements needed to sustain ecosystem function.

Green water: Root-zone soil moisture contributed by precipitation that is available for plant uptake.

Blue water: Fresh water in surface and groundwater bodies that is available for human use (including irrigation).

Sustainable irrigation: An irrigation practice that does not deplete environmental flows or groundwater stocks.

Deficit irrigation: An irrigation practice that meets only part of crop water requirements while leaving crops in moderate water stress conditions.

Equations (1) and (2) thus offer one way to define a "ceiling" of maximum water consumption, which we show below. Because scenarios with expansion of agriculture into other ecosystems (e.g., forests, grasslands) would likely be unacceptable from the standpoint of environmental sustainability due to habitat destruction, biodiversity loss, and carbon emissions (Godfray et al. 2010, Foley et al. 2011), we concentrate on the expansion of irrigation to rainfed cultivated areas and keep unchanged the spatial extent of cultivated land. It is important to recognize, however, that even in the absence of agricultural expansion, the rights of waters may be undermined by loss of environmental flows below a level critical to the functioning of aquatic ecosystems. We express the far terminus of that direction with a scenario with zero environmental flows (EF=0). In that case, the values represented by rights of waters are completely sacrificed.

The IWC sufficient to meet the human right to food for all people depends on global population size (P) and the average per capita blue water footprint (BWF), i.e. the amount, per capita, of irrigation water needed to increasing food production above the background rainfed level. A minimum well-being value (BWF_{min}) multiplied by the population thus gives a bare minimum IWC requirement, or the 'floor' of water consumption by human societies.

That represents, however, the most water-austere diet and universal equality in adopting it. Accounting for values exhibited by actual social choices and consumer behavior (including food waste and type of diet) requires considering a greater (average) per capita blue water footprint $BWF = \varphi \times BWF_{min}$ with φ

>1 as an inflation factor that captures spatial variability in the adoption of water-conservative versus water-demanding food consumption patterns. We use the inflation factor to represent the fact that use of water for food by those already above BWF_{min} is not expected to decrease, while the minimum level of water consumption for food in the undernourished part of the population must increase to meet human rights. Therefore, any inequality within countries would be reflected in a value of $\varphi > 1$ to account for the fact that some citizens consume more than $\mathrm{BWF}_{\mathrm{min}}$.

The *IWC* requirement thus depends on pathways of socio-economic development (see methods). The actual *BWF* is a function of consumption choices (e.g., dietary preferences and food waste rates), with variability in that value around the world reflecting global inequality. Thus, we use the inflation factor φ to account for the fact that water requirements vary with dietary choices (e.g., animal food requires much more water than plant food, on a per food calorie basis) and food waste (about 25% of the food produced worldwide is wasted (Kummu et al. 2012)). Thus, to meet the water requirements for human rights to food irrigation water consumption, *IWC*, will need to exceed the value

$$IWC \geq \varphi\ \times BWF_{min} \times P \qquad (3)$$

in addition to relying on rainwater (green water) for the rainfed fraction of agricultural production.

Again, the human rights to food could in principle be met with φ=1 everywhere (absolute equality in a water-austere diet). And, of course, societies could choose against the commitment to protect human rights for all. Opting for more likely combinations of social choices around inequality and consumption, our model expresses a human right to water that accounts for social preferences for more water-intensive diets while ensuring that every human has access to food equal to BWF_{min}. In these analyses, BWF_{min} is kept constant while the factor φ, which depends on the fraction of the diet contributed by animal products and food waste, is region-specific and varies as a function of the pathway of socioeconomic development (Beltran-Peña et al. 2020).

We can then express the relation of several different values comprising water security thus:

$$\varphi\ \times BWF_{min} \times P \leq IWC \leq IWC_{max} \qquad (4)$$

On this representation, ($\varphi \times BWF_{min} \times P$) expresses the right to water, and may be thought of as a realistic floor of justice, while (IWC_{max}) expresses the relative weight of rights of waters through the specification of EF values in equation (2), and might be conceived of as a ceiling of sustainability (or “planetary boundary” for water). Notice that in this paper “justice” denotes a condition in which human rights are met. Therefore, justice can co-exist with inequality as long as everyone has access to at least a minimum amount of resources (i.e., BWF_{min}) to meet their human rights to food (see also D’Odorico et al., 2019). Both ceiling and floor are not hard limits but variable according to values-based social choices. While of course there are biophysical limits to both, those correspond to unlikely social choices: absolute equality in a water-minimum diet on one hand, and consumption of all water without regard for ecological (or cultural) function on the other. In other words, the contest of social values plays a role in determining the relative ceiling and floor.

In this study we depict floor and ceiling under different values-based scenarios and investigate the extent to which the gap between floor and ceiling is shrinking. “Rights to water” vary with dietary choices, food waste habits, acceptance of social inequalities, and demographic change. “Rights of waters” depend on the extent to which environmental flows are valued. “Commercial water rights” for non-food economic uses are represented in equation (1) through the OU variable representing “other uses”.

The water balance analysis in equation (1) is carried out at the annual time scale without considering the possible emergence of seasonal water scarcity, which may be dealt with in some regions by using water storage from aquifers and reservoirs, nor the possibility for over-year storage to overcome annual water shortages. Both seasonal and interannual variability, however, could in principle be integrated into this framework. The key point is that estimating the hydrological entailments of different ways of valuing water can facilitate open deliberation of those values and advance understanding of what choices may reduce conflicts between them. A more detailed description of the model is presented in the Methods section at the end of this article.

Results and Discussion

We show how water security is related to social and environmental values for water. Limits to plausible conceptions of water security are largely determined by decisions made about environmental flows (*EF*) and about irrigation (Poff et al., 1997). We explain those limits by illustrating several conceptions of a hydrological boundary, as derived from several different value premises.

To represent three different social values for the rights of waters, we model three different *EF* thresholds. Environmental flows are initially set equal to 80% of runoff as in Richter et al. (2012). We then consider a less conservative scenario that allows for a more intense use of water for human activities with only 20% of total runoff protected as environmental flows (i.e., unlike the previous scenario, in this case the majority of water goes to human activities), as well as a scenario of complete disregard of environmental needs in which *EF* are set to zero. In other words, we have chosen some “end-member cases” (80%, 20% and 0%) but of course the same framework could be used to model the entire range in between them. The environmental impacts of these *EF* scenarios are difficult to evaluate at the global scale because they are specific to streams and watersheds. Based on analysis of multiple case studies, Richter et al. (2012) indicated that flow reduction to 80% of the natural streamflow regime would be associated with measurable changes in the natural structure but minimal alterations to the function of riverine ecosystems. Based on that research, we specify 80% of runoff as an *EF* proxy for rights of waters; that is, a relatively lower “ceiling.” In that scenario, about 514 km^3 y^{-1} can be consumed for irrigation in the land that was irrigated in 2000. But if irrigation is expanded to areas that are currently rainfed, irrigation water consumption would more than double, reaching 1,179 km^3 y^{-1}. Expanding irrigation to areas in which only a fraction of the irrigation water requirements can be met would further increase the volume; to 1301 km^3 y^{-1} with 30% deficit irrigation (i.e., with 30% of the irrigation water requirements remaining unmet).

With a less robust *EF* proxy for the rights of waters, however, societies may raise the ceiling (i.e., the maximum allowable rate of water use). For instance, if environmental flows are set very low, as 20% of total runoff, room for global irrigation water consumption increases to 2,031 km^3 y^{-1} (Table 1). These conditions, however, would likely cause ecological impairment of the aquatic system (Arthington et al., 2006). Because societies could conceivably choose not to recognize any of the values encompassed in rights of waters, we also depict an extreme case in which *EF* are set to zero. In that extreme limit case, “space” for irrigation water consumption increases to 2,510 km^3 y^{-1} (Figure 1). This analysis was carried out starting from an evaluation of local constraints (equation (1)) to calculate the maximum allowable rates of global water consumption (equation (2)) that is compatible with different environmental flow scenarios. Therefore, these global values are estimated ensuring that locally the environmental flow limits are not exceeded.

Our estimates for 2020 indicate that human consumption of freshwater for irrigation accounts for 1117 $km^3 y^{-1}$ (Table 2). The most robust conception of rights of waters considered in this study, at 80% *EF*, is therefore feasible, though with very tight margins (1179 $km^3 y^{-1}$ with expansion into rainfed areas and no deficit irrigation and 1301 $km^3 y^{-1}$ with 30% deficit irrigation). Indeed, as we show (Figure 1), these margins are too small to accommodate growth in water demand for agriculture in the next few decades. These levels of water consumption for irrigation cannot be met within the current footprint of areas equipped for irrigation without competing with environmental flows. Only part of the irrigation water needs (i.e., 514 $km^3 y^{-1}$ out of 1117 $km^3 y^{-1}$) can be met while sustaining *EF* at 80% of runoff and without expanding present areal irrigation footprint (Table 1).

That result means that today about one half of the irrigation water demand is met at the expense of environmental flows. It does not, however, imply that societies, in order to protect commitments to justice, would be compelled to choose the weak conception of rights of waters at 20% *EF*. In fact, as noted earlier, expanding irrigation to suitable rainfed croplands would make it possible to meet these irrigation water needs, while removing current irrigation from areas where it occurs at the expense of environmental flows. Figure 1 shows the "hydrological space" above a floor of justice (Table 2) for realizing greater *EF*.

To calculate the irrigation water required to sustain human food demand above a water-austere minimum, we consider the population growth projections developed by the United Nations under three different demographic scenarios ("low, "medium" and "high" population, see methods). These projections are paired with three shared socio-economic pathway (SSP) scenarios, corresponding to "sustainability" (SSP1), "middle of the road" (SSP2), and "regional rivalry" (SSP3) pathways, which give an estimate of the degree of reliance on animal products, while accounting for the effect of inequalities (O'Neill et al., 2017). These shared socio-economic pathways are used to represent the way humanity as a whole may either become more conservative in the use of water for food or, on the other hand, increase per capita water consumption through food production, as most societies have been doing. While the SSPs are narratives of global trends not of different cultural values, we can use SSPs to represent possible changes in consumption habits (e.g., diet, population) and associated inequalities (O'Neill, et al., 2017) that account for the integrated effect (at the country scale) of individual choices driven and informed by a variety of factors, including cultural values.

We specify the inflation factor (φ) – which, again captures global inequality in water consumption for food due to dietary choices and food waste patterns – by using these three scenarios to represent region-specific social preferences for more water-intensive diets (Beltran-Peña et al. 2020). We then use those parameters to calculate the corresponding (average) irrigation water consumption per capita (see Methods). The sustainability pathway (which reflects less demanding dietary and food waste choices) combined with the low population scenario shows (Table 2) a decline both in population and water demand by the end of the century and a peak in 2050 with volumes that remain well below the "ceilings" in Table 1 (see Figure 1). Conversely, the middle of the road pathway combined with medium population growth shows an increase in both population and per capita water demand throughout the 21st century.

By 2100, this scenario reaches conditions inconsistent with robust-to-moderate values of environmental flows (e.g., *EF*=80% or 20% of runoff, respectively), representing different conceptions of the rights of waters, shown as ceilings in Figure 1. The so-called "regional rivalry" pathway (SSP3) corresponds to a world with high per capita consumption rates and little attention to global needs (Riahi et al. 2017). This pathway, combined with the high population growth scenario provides dystopic projections of overshooting, with the global population in excess of 15 billion people and irrigation water demands greater than 5 times the ceilings associated with robust-to-moderate rights of waters scenarios (Tables 1 and 2).

Working with these socio-economic pathways helps illustrate that, as both per capita consumption and population grow, the floor of justice rises, narrowing hydrological space available for other important forms for valuing water, such as the relational and intrinsic values associated with environmental flows (i.e., *EF*) and as resources for businesses (i.e., *OU*). This analysis, however, does not account for the way the development of new technologies and farming practices would partly overcome water limitations (Boserup, 1981). Indeed, the efficiency of water use may be improved by changing the crop distribution (i.e., planting the right crop in the right place (Davis et al., 2017)), adopting soil water conservation methods (including more efficient irrigation systems) that reduce soil evaporation, or though "more crop per drop" technology (Falkenmark and Rockstrom, 2004). Despite these possible improvements, water limitations remain a major constraint to humanity's ability to meet the increasing need for food commodities (e.g., Jagermeyr et al., 2015; Gerten et al., 2020).

At a planetary scale, water use by business operations and municipal needs – here accounted for through the *OU* term in (1) – do not substantially affect global food production. At the local scale, however, they can be quite important, particularly when cities and other residential areas encroach into agricultural areas in arid or semiarid regions (e.g., Las Vegas, Los Angeles), or when industrial operations such as energy production and mining are established in water-stressed areas (Bonnafous et al. 2017, Rosa et al. 2018b). At a local scale, commercial and municipal water uses often compete with subsistence farming and rural livelihoods, thus impacting the food security of rural communities, particularly in densely populated or water-scarce regions where water demand from these uses (*OU*) is a substantial fraction of availability (Figure 2).

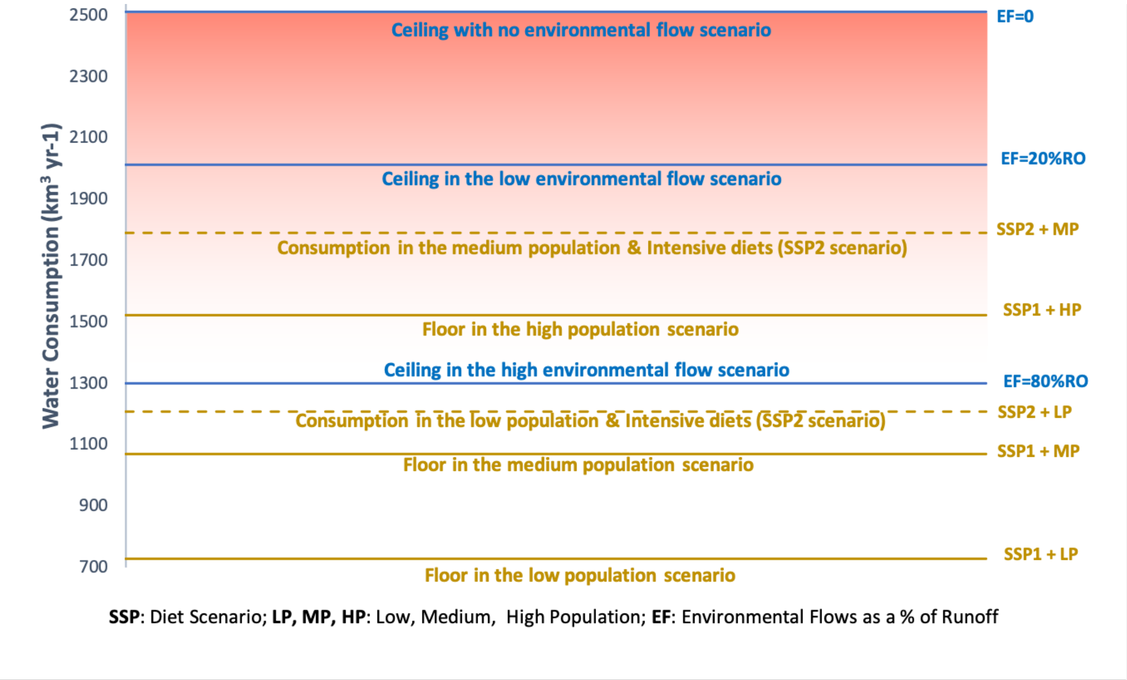

Figure 1*. Different ‘floor’ and ‘ceiling’ levels in the various scenarios included in this study. The ceilings (in blue) represent biophysical limits imposed by the global water availability, as determined by the way societies value the ecosystem functions that depend on them (Table 1). These limits, which are here estimated considering a 30% deficit irrigation, depend on the choices we make on environmental flow (EF) requirements. The consumption levels (brown lines) account for water demand to meet human needs associated with food consumption. These levels vary with population size, dietary choices (i.e., reliance on animal food), food waste, and inequality (Table 2). We use solid brown lines, for the least demanding per capita consumption scenario (SSP1), which represents what we call the ‘floor’, i.e., the consumption levels to meet primary food needs for a given population size. The combination of scenarios associated with different ceiling and floor levels determine the space between floor and ceiling; or a values-based conception of ‘safe and just operating space’. The ceiling levels associated with environmental flows between 0 and 20% of runoff correspond to undesirable conditions of loss of aquatic habitat. The SSP1 diet scenario combined with low and mid 2100 population scenarios are suitable for all the ceiling scenarios. EF corresponding to 20% of local runoff are suitable for all the SSP1 diet scenarios as well as SSP2 with low and mid population. Some floor-ceiling scenarios exhibit floors higher than the ceiling, meaning that the water resources of the planet are not sufficient to meet human demands. Indeed, in the SSP2 and SSP3 diets (not shown, see Table 2) combined with high 2100 population scenarios, food demand would overshoot the most conservative biophysical limit (with 80% EF) in year 2050 and 2100. If met, such demands would run rivers dry.*

Table 1. Limits (or “planetary boundaries”) to irrigation water consumption. *High and low environmental flow scenarios correspond to the case with EF equal to 80% (Richter et al., 2012) or 20% of runoff, respectively. We calculate the limit to water consumption in land equipped with irrigation (based on data from circa 2000) and in rainfed cropland suitable for irrigation. We also consider the case in*

which irrigation is practiced in areas in which only at most 70% of the irrigation water requirements are met, leaving 30% of crop needs unmet (30% water stress).

		Irrigation Water Consumption in year 2000 (km^3 yr^{-1})		
	Environmental Flow (EF) Scenario	**80% to EF**	**20% to EF**	**“NO” EF**
With NO Deficit Irrigation	*Water consumption in land equipped for irrigation in year 2000* (Rosa et al., 2019)	*514*	*775*	*843*
	Potential irrigation expansion	*665*	*1,201*	*1,550*
	LIMIT TO IRRIGATION	**1,179**	**1,976**	**2,393**
With 30% Deficit Irrigation	*Water consumption in land equipped for irrigation in year 2000*	*540*	*801*	*880*
	Potential irrigation expansion	*761*	*1,230*	*1,630*
	LIMIT TO IRRIGATION	**1,301**	**2,031**	**2,510**

Table 2. Irrigation water required to meet human demand for food. *Values in italic fonts refer to 2050, in boldface to **2100**. Based on the limits in Table 1, we highlight in green the combinations of population scenarios and shared socioeconomic pathways that are well within the just and sustainable operating space (i.e., using a robust conception of environmental flows); we highlight in red the combinations that would be unsustainable even using the environmentally less conservative definition of environmental flows. Intermediate conditions are highlighted in yellow.*

Population (Billion)	**Low**	**Medium**	**High**
2020		7.78	
2050 **2100**	*8.88* **7.30**	*9.71* **10.84**	*10.56* **15.55**
Global irrigation water demand (km^3 yr^{-1})			
2020		1,117	
SSP1	*970* **728**	*1,059* **1,069**	*1,150* **1,521**
SSP2	*1,354* **1,208**	*1,479* **1,790**	*1,607* **2,565**
SSP3	*3,310* **3,709**	*3,605* **5,549**	*3,907* **8,017**

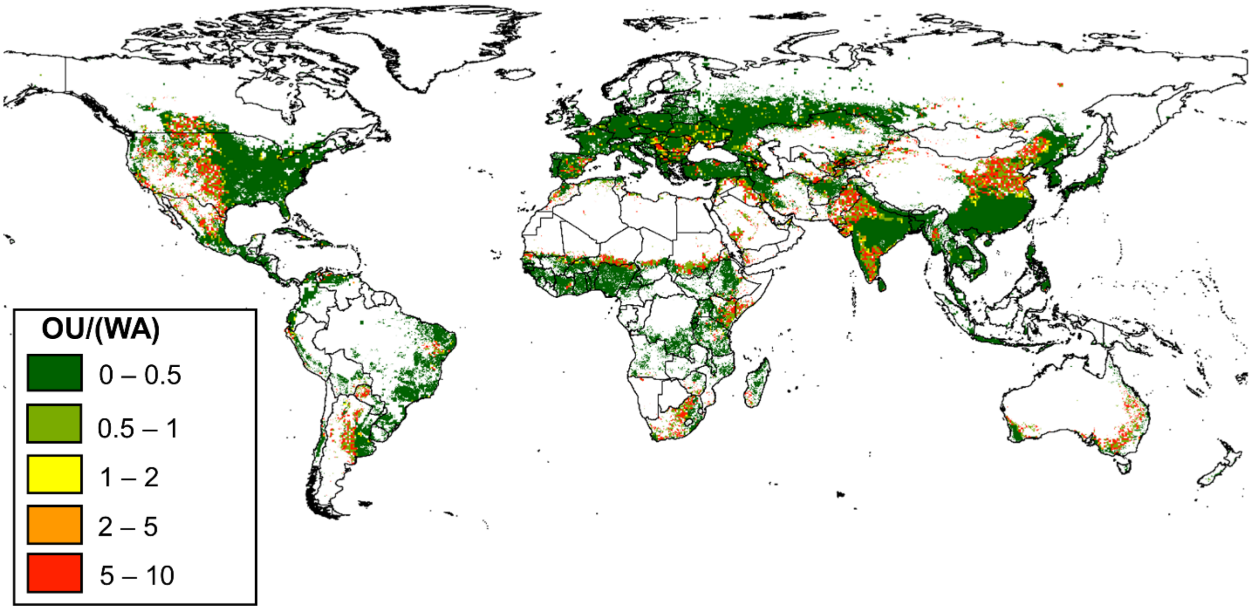

Figure 2. Fraction of available blue water (WA) allocated to other (non-agricultural) uses (OU), including municipal and industrial uses*. Irrigation water consumption data are from Rosa et al. (2020). Other uses data are from Hoekstra and Mekonnen (2012). Values greater than one correspond to overuse (i.e., non-agricultural uses exceed water availability).*

Conclusion

Assessments of water security should incorporate the implications of different value scenarios – including different *kinds* of values—and hydrological models can do so, as illustrated herein. A pluralist approach can recognize multiple water values while still affording comparison and combination of value regimes by showing their hydrologic implications. Rather than presenting an optimizing equation, the results of this study present a range of illustrative outcomes for different value and use scenarios. This approach does not solve for one conception of water security because it does not select one mode of value (e.g., welfare efficiency) into which others are 'integrated' or reduced. The point to this exercise is not to lay out one pathway for ensuring water security, but to expand and diversify conceptions of water security while also stimulating critical reflection on the values underlying those conceptions by modeling their hydrological implications.

A pluralist approach seems in line with the depth of cultural work involved in meeting resilience challenges. Rockstrom et al. (2014: 1257) write: "a transformation to the sustainable use and management of water and ecosystem services… will require experimentation with resilience-based approaches to integrated water-resource management and ultimately a deep mind shift towards a new socio-ecological water paradigm, where stewardship of water in support of human prosperity is pursued within the safe operating space of a stable planet." Our framework supposes that experimentation with multiple approaches may help drive the sort of cultural examination involved in "deep mind shift." If cultural reform may be stimulated by adaptive experiments made from a wide range of values (Jenkins 2011), then depicting the hydrological entailments of values involved in making those experiments can help inform and perhaps deepen deliberation. It also advances understanding of a "safe operating space” in which to conduct such experiments (Figure 1). Water security ideas become more robust as they become more pluralist, and water security frameworks become more useful to governance debates as they become more capable of facilitating deliberation over values in relation to their hydrological implications.

Methods

Assessment of maximum irrigation water consumption compatible with environmental flow scenarios

We calculated maximum potential irrigation water consumption for global croplands compatible with environmental flow requirements (here used to represent ecocentric and cultural rights of waters) by combining local "blue water" (i.e., water from surface water bodies or aquifers) availability with current and potential blue water consumption for irrigation. Specifically, we use a water balance approach to calculate the runoff (i.e., the sum of surface and subsurface runoff) that is generated at each location. Blue water availability is determined as the difference between runoff estimates and environmental flows (Eq. (1)). If the local water consumption exceeds the renewable blue water availability, it means that it either causes a loss of environmental flows or of groundwater stocks. Thus, the planetary boundary for freshwater is overshot when total human blue water consumption for human needs (irrigation plus other uses) exceeds blue water availability. Under these conditions, irrigation practices are considered unsustainable because they are depleting environmental flows and/or groundwater stocks (Rosa et al. 2019). We focus on agricultural regions of the world and their upstream watersheds using a square grid of 50 km resolution. We evaluate equation (1) (see main text) for every 50 km x 50 km site, *i*. The local runoff, RO_i, is calculated based on long term (circa year 2000) runoff estimates from the Composite Runoff V1.0 database (Fekete et al. 2002) and the upstream-downstream routing "flow accumulation" function in ArcGIS®, accounting for the effect of upstream withdrawals on downstream runoff (Rosa et al. 2018a). Environmental flow requirements, *EF*, were assessed by using a 0%, 20% and 80% threshold, i.e. assuming 100%, 80% and 20%, respectively of local water availability could be used by irrigation, industrial, and municipal activities. This approach allows for an assessment of the planetary boundaries for water (Table 1) that accounts for local-scale environmental flow constraints.

Baseline and potential irrigation blue water consumption were taken from Rosa et al. (2020) and were assessed using a global crop water model (Chiarelli et al. 2020) run with climate forcing for the 1996-2005 period, while keeping the spatial extent of global croplands fixed to the MIRCA2000 dataset (Portmann et al. 2010). In every grid cell, the baseline irrigation water consumption was calculated by multiplying the crop-specific blue water requirement by the irrigated harvested area of that crop in the year 2000 (Portmann et al. 2010). For each crop, we also assessed the potential irrigation water consumption at yield gap closure - the difference between current and maximum attainable yields (Van Ittersum et al. 2013) - by multiplying crop-specific blue water requirements by the rain-fed harvested area of that crop in the year 2000 (Portmann et al. 2010). Irrigation water consumption at yield gap closure is the additional irrigation water necessary to avoid water-stressed plant growth and therefore reach maximum crop productivity (or 'close the yield gap') in rain-fed croplands. In this analysis we used 26 major crops and crop classes, that account for nearly 100% of global crop production (Rosa et al. 2020).

Total water consumption was assessed (Eq. (1)) by summing yearly irrigation water consumption and yearly estimates of industrial and municipal blue water consumption (Hoekstra and Mekonnen

2012). Because farmers might not always irrigate at maximum potential, to assess the planetary boundary for freshwater over global croplands, we also considered a 30% deficit irrigation scenario, where only 70% of full irrigation water requirements are applied to crops. Thus, in the 30% deficit irrigation scenario, irrigation is practiced also in areas where only a fraction (up to 70% in this case) of the irrigation water requirements can be met with the local water availability. Thus, this latter scenario entails a greater irrigation water consumption than the case with no deficit irrigation. Deficit irrigation is an irrigation practice whereby irrigation water supply is reduced below maximum levels and crops are grown under mild water stress conditions with a linear reduction in crop yields, proportional to the reduction in water application (Rosa et al. 2020). The model calculates irrigation water requirements at the annual time scale and does not engage in an analysis of water scarcity at the monthly time scale because seasonal water deficits can be mitigated by water storages (in the groundwater and in surface water reservoirs) as long as at the annual scale irrigation water demand does not exceed the availability.

Assessment of population-based planetary boundaries for freshwater

Blue water required to meet food demand, D (kcal), in the 21st century was assessed by considering the water footprint of projected diets. Projected diets and the fraction, q, of kilocalorie intake from animal products were taken from Beltran-Peña et al. (2020) and assessed considering future projections in dietary changes according to different socio-economic scenarios and UN population prospects (Beltran- Peña et al. 2020). To account for the greater water footprint of animal food than plant food, the total water footprint of projected diets was calculated as :

$$WF_{DIET} = D \times (1-q) \times WF_{Plant} + D \times q \times WF_{Animal},$$

where $WF_{Plant} = 0.5\times10^{-3}$ m^3/kcal and $WF_{Animal} = 4\times10^{-3}$ m^3/kcal are the average water footprints of plant and animal-based foods (Falkenmark and Rockström 2004). Projected diets (i.e., the fraction of diet from plant-based and animal-based products) were taken from Beltran-Peña et al. 2020 and assessed using Integrated Assessment Models (IAMs) and diets projections associated with different Shared Socioeconomic Pathways (SSPs) projections (Riahi et al. 2017). Because a fraction $r \approx 15\%$ of total water consumption (green+blue) in agriculture is from blue water (Rosa et al. 2020), the blue water footprint of diets was estimated as

$$BWF = r\, WF_{DIET}$$

In other words the irrigation water consumption to meet human food needs can be calculated as $IWC = BWF \times P$, where *P* is the global population, and expressed as a multiple of the minimum well-being requirement as explained in the text (see eq. (3)). We use three demographic scenarios from United Nations (U.N., 2019), corresponding to low, medium, and high growth. For future dietary projections, we follow Beltran-Peña et al. (2020), who developed an algorithm to predict region-specific plant-based and animal-based diet compositions (i.e., the factor *q*) until 2100, based on the SSP scenarios. The factor φ was then estimated as the ratio between *BWF* and BWF_{min}, accounting for dietary choices in excess of the minimal requirements. As φ varies across the globe, this also captures inequalities within and across countries (O'Neill et al., 2017).

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