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The Water Crisis by the Global Commission on the Economics of Water: A Totalising Narrative Built on Shaky Numbers

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ABSTRACT: Reports by the 2023 Global Commission on the Economics of Water (GCEW) claim that a global water crisis is underway because the world is close to its upper planetary boundary for water. We contend that these reports are flawed in two distinct ways: 1) their use of the planetary boundaries framework as a sweeping narrative lacks justification, ignores alternative framings and disregards scale; and 2) their numeracy is substandard, with arithmetic errors and overstated numerical accuracy. These flaws cast a shadow on the GCEW's capacity to convey robust knowledge about the water cycle and water scarcity. Rather than acting as an honest broker to explore potential policy scenarios based on our best available water science, the GCEW resembles an instrument to further the planetary boundaries framework and its associated scientific, political and economic interests.

KEYWORDS: Planetary boundaries, irrigation, water cycle, modelling, uncertainty

INTRODUCTION

The Global Commission on the Economics of Water (GCEW) is a major water policy enterprise comprising a website and a set of reports (https://watercommission.org; GCEW, 2023; Mazzucato et al., 2023). Launched in May 2022 with a two-year mandate, the Commission is convened by the Government of the Netherlands and facilitated by the Organisation for Economic Co-operation and Development (OECD). Through the use of scientific evidence, the GCEW aims to facilitate large-scale public–private partnerships and economic changes to ensure a sustainable water future for all (Ministerie van Infrastructuur en Waterstaat, 2023). According to the GCEW, their aim is to "make a significant and ambitious contribution to the global effort to spur change in the way societies govern, use and value water" (GCEW, 2023: 96).

Its Phase 1 report, issued in March 2023, argues that we face a systemic water crisis and calls for a fundamental shift in our understanding of water that will "redefine the way we value and govern water for the common good". The GCEW's demand for a renewed global effort to improve water governance is based on their claim that a global water crisis is underway. If left unaddressed, they say, "no person, place, economy or ecosystem will be spared" (ibid: 6). It arrives at this conclusion by affirming that humans are close to exceeding the safe operating space of the planetary boundaries for water use (ibid: 10) and that our actions have pushed the global water cycle out of balance (Mazzucato et al., 2023: 6).

In this paper, we analyse the research design underlying the GCEW's announcement of an impending water crisis. We especially consider its conceptual framework, its narrative, and its use of numbers. We concentrate on the GCEW's executive, main and technical reports (respectively, Mazzucato et al., 2023;

GCEW, 2023; Grafton et al., 2023), and we examine how the GCEW's global water crisis narrative retains the confidence of a scientific audience.

To cover both qualitative and quantitative uncertainties, we examine the GCEW's claims through the lenses of sensitivity auditing (SAUD) and uncertainty and sensitivity analysis (UA/SA). SAUD is a practice of organised skepticism that is used to assess the rigour and transparency of scientific evidence for policy-making. It examines the ambiguities, underlying narratives and hidden premises that escape classic uncertainty analyses due to their qualitative nature (Saltelli et al., 2013; Lo Piano et al., 2022). UA/SA, in contrast, focuses on the quantitative dimension by examining whether model-based numbers are robust against uncertainties and alternative model formulations (Saltelli et al., 2008). Both approaches aim to clarify the dependency of model-based inferences on model assumptions, enhancing transparency and fostering plurality for decision-making. UA/SA and SAUD are recommended by the European Commission (2023) and the European Science Academies (SAPEA, 2019) when model-based research feeds into potentially contested policy arenas.

Our results suggest that GCEW's account of the global water crisis is a totalising narrative based on a weak reading of the existing literature, poor treatment of scale, wrong arithmetics, disregard of uncertainties and selective data gathering, and that this has led to the production of numbers without internal consistency. In other words: the GCEW reports are defective in their setting of a research design to frame, communicate and provide evidence for a global water crisis. It is important to note that this observation does not lead us to refute the presence of significant local-scale water insecurities due to increasing water demand, droughts and floods (Zeitoun et al., 2016; Scott et al., 2021; Vörösmarty et al., 2010). Such challenges exist, they are serious and demand swift addressing. Rather, what our work suggests is that the global water crisis, in the terms posed by the GCEW, does not stand up to scrutiny. This fact raises doubts as to whether the GCEW's goal is to convey reliable knowledge about water management or to offer pseudo-scientific support to uphold predetermined academic and political interests.

A SUMMARY OF GCEW'S CLAIM OF A GLOBAL WATER CRISIS

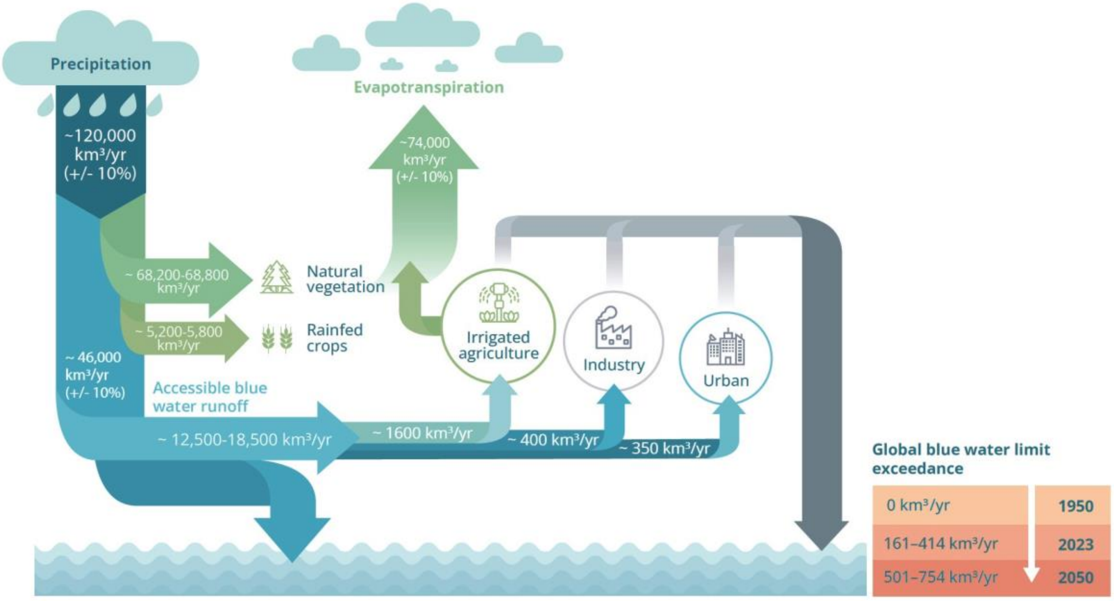
There are two explanatory concepts in the GCEW framing of a global water crisis. The first is the "water cycle" (GCEW, 2023: 8) and the second is a "safe operating space" (ibid: 10), the latter being a term drawn from the planetary boundaries (PB) framework (Rockström et al., 2009). According to the Stockholm Resilience Centre, the PB concept "presents a set of nine planetary boundaries [including the freshwater PB] within which humanity can continue to develop and thrive for generations to come". We can read in the main GCEW report (2023: 10) that "a starting point is to define the safe space in which societies can satisfy their water needs (lower boundary) while ensuring the water cycle remains within a manageable range (upper boundary)".

The GCEW's water cycle concept is illustrated in Figure 1. Starting with precipitation inputs, the depiction follows with the amount of water consumed by natural vegetation and rainfed crops (green water) and the total global land water runoff, of which only a fraction is accessible for irrigated agriculture, industry and urban uses. The grey arrows exiting these three water sectors represent the fraction of water that enters a stream/aquifer and is available for reuse. The infographic is so relevant in the narrative of the GCEW that a technical report detailing the calculations, and the data sources used to ground it, has also been published (Grafton et al., 2023).

As for the 'safe operating space', the GCEW sets the lower boundary at approximately 1200 cubic metres per year per person (m^3/yr/person). Although they do not explicitly justify why they have selected this threshold, the number is supposed to cover the minimum water required for cooking, drinking and sanitation, but also the green and blue water serving other human needs such as the production of food and fibre (GCEW, 2023: 10). The upper boundary is left undefined; however, the GCEW quantifies the extent to which this upper boundary has been transgressed, specifically for the years 1950 (0 km^3/yr), 2023 (161 to 414 km^3/yr) and 2050 (501 to 754 km^3/yr) (see the orange table in Figure 1).

In the following sections, we review the GCEW's understanding of the water cycle within the planetary boundaries framework and their claim that there is a global water crisis under way. We then conduct a UA/SA on the model-based numbers that ground the GCEW's assertion that we have breached humanity's safe space for sustainable freshwater management. Finally, in the discussion and conclusion sections, we reflect on why the GCEW's failure to come to terms with uncertainties undermines its credibility as an institution that aims to leverage the best science available to tackle the water challenges of today.

Figure 1. GCEW's water cycle concept, including global water consumption by sector and blue water consumption exceedance.



Source: GCEW (2023), Figure 2.2. Reproduced with permission.

Note: GCEW = Global Commission on the Economics of Water.

THE GCEW'S THEORISATION OF A GLOBAL WATER CRISIS

We believe the GCEW reports suffer from four main framing problems: 1) uncritical acceptance of the PB framework as a sweeping narrative, thus neglecting alternative conceptualisations of a water crisis and limiting debate; 2) insufficient reflection on scale dynamics and water scarcity; 3) unclear translation of the PB narrative into effective policies; and 4) ambiguity in characterising green/blue water and consumptive/non-consumptive water use.

Planetary boundaries as a totalising narrative frame

We cannot find any text explaining why the PB framework was selected as the conceptual framework for understanding water at a global level. Our interpretation of this omission is that the GCEW assumed readers would readily accept the PB framework as the only possible paradigm to conceptualise and quantify what is safe (below the upper boundary) or critical (exceeding the upper boundary). This methodological blackout disregards a critical audience and sidesteps alternative framings whose theoretical background and insights may not necessarily have aligned with those provided by the PB framework.

A global water crisis, for example, can also stem from changes in physical parameters caused by variations in water supply and demand at regional scales, such as catchments (Molden, 2009). Within this framework, water is primarily analysed via hydrological change, an approach that has formidable empirical backing in the literature (Blöschl et al., 2019; Vörösmarty et al., 2010). The GCEW could have investigated global water using local parameters such as zero- or low-flow exceedance for rivers, pollution loads, regional soil moisture deficits, flow threshold behaviour and water storage anomalies (Vörösmarty et al., 2010; Nathan et al., 2019). The global crisis would have then been framed as the sum of mainly local – and thus potentially solvable – crises. Furthermore, a global water crisis can also be constructed as country-level water insecurity that is observable in the form of supply – demand water quantity and quality imbalances and their associated risks. Grey and Sadoff (2007) took this approach, although they did not escape criticism for the way they rendered complex spatial and temporal hydrological data into summary statistics. The topic of scale is relevant and is one that we will return to below.

Other guiding theories would have generated different approaches and supporting literature. These could include, for instance, a multifaceted view of water security (Zeitoun et al., 2016), a political viewpoint (Allan, 2012), a socio-hydrological viewpoint (Mao et al., 2017; Budds et al., 2014), or a 'capacities' interpretation (Ohlsson, 2000; Wolfe and Brooks, 2003). The last of these would have allowed the GCEW to argue that the crisis is one of inadequate management that, in turn, requires very different numbers to describe it, such as declining investments, training, or ministry staff numbers.

Had the GCEW referred to some alternative conceptualisations of a water crisis, it would have become clear that the PB framework is merely one narrative chosen from a pool of many possible options. The lack of justification for the adoption of the planetary boundaries framework is puzzling given that many scientists are aware of, and are involved in, knowledge contestation regarding water and water policies (Boelens et al., 2019; Mollinga, 2008). While embraced by many scholars, the PB model has also been widely criticised for oversimplifying non-commensurate and complex phenomena into a one-dimensional term, struggling with clear scientific operationalisation and comparing against arbitrary baselines. As a result of these shortcomings, the PB framework has faced significant challenges in obtaining unequivocal empirical support (Montoya et al., 2018a, 2018b). None of these criticisms are acknowledged in the GCEW report.

With regard to non-commensurability, for example, the 'climate PB' is a threshold that arises from the complex interactions of several atmospheric phenomena, whereas the 'phosphorus PB' refers to a single soil nutrient that recycles poorly back into soil. The 'groundwater PB' is also problematic. In Rockström et al. (2023a), the safe Earth system boundary (ESB) for groundwater aquifers is defined on the basis of their average annual recharge: if drawdown is less than recharge, the aquifer is within the ESB.[1] This emphasis on both recharge and an annual time frame, however, depends on highly variable local characteristics of the aquifer in terms of water demand and specific impacts (Foster et al., 2013). In certain areas, fossil volumes remain unreplenished, thus rendering recharge rates less crucial as the determining factor. In other places, recharge is either very difficult to measure or highly variable over time and space. Such areas, in defining sustainable use, would benefit from intra-annual seasonal measurements (Jasechko et al., 2014) or from appraisal at decadal, rather than annual, time scales (Taylor et al., 2009).

[1] According to Molle (2023: 293), the assumption that over-exploitation occurs when groundwater abstraction exceeds recharge suffers from two main drawbacks. First, it takes for granted that there is a clear threshold beyond which an aquifer is over-exploited, and that this threshold equals its recharge. And second, it overlooks the point that balancing withdrawals with recharge draws all outflows to zero over time, with critical impacts on surface water and ecosystems.

The GCEW's report also appears to neglect the fact that the definition of the 'freshwater PB' has undergone numerous revisions since its establishment 15 years ago. This inconsistency underscores the fragility of its empirical foundation. Initially set at 4000 to 6000 km^3/yr (Rockström et al., 2009, Table 1), it has recently been redefined at 7630 km^3/yr (or alteration of <20% of water flows compared to natural river flow regime) (Rockström et al., 2023a: 4). By the time we revised this paper after peer review, a new study had set the upper end of the freshwater PB at the 95th percentile of pre-industrial variability in global land area with local streamflow (blue water) and soil moisture (green water) deviations (Porkka et al., 2024: 264). We have found no indication as to why this percentile – and not the 90th, 80th or any other – should be chosen as the threshold.

The problem seems also to be one of scale: Heistermann (2017) argued that, although proponents of the freshwater PB assumed that a global threshold can be exceeded due to aggregation of impacts at the regional level, PB proponents failed to provide evidence of how freshwater use could trigger the collapse of regional or continental water cycles. And even if they could muster this evidence, the problem would persist because a global freshwater PB can never accurately reflect the regional thresholds beyond which a freshwater system collapse might occur.

The elusive nature of the freshwater PB is especially apparent in the conceptualisation of the GCEW's lower and upper global water boundaries (GCEW, 2023). They are simultaneously defined as a range (ibid: 19) and as a volume-per-person limit (in m^3, lower boundary) or a global limit (in km^3) (ibid: 10). They are also defined in terms of a supply figure as precipitation (ibid: 10) and as a global blue and green water-use figure (ibid: 10). Especially confusing is the fact that the lower and the upper global blue water boundaries cannot be compared. This is because the lower boundary is a water demand figure given in m^3/yr/person, while the upper boundary is a water supply number given in annual km^3. In the section "The innumeracy of GCEW's approach to quantification", we will see how this loose conceptualisation rests on equally disconcerting numbers.

Poor treatment of scale in the global water crisis

By selecting a unitary whole-planet scale, the GCEW does not discuss how scales interact and how scale-nesting reveals water shortfalls and limits. At lower scales (catchments and below), shortfalls express themselves in the form of a mismatch between supply and demand over time and space. A catchment thus experiences water scarcity because, in the case of a drought, its expected demand is no longer matched by expected supply. Within (beneath) the catchment scale, spatial and temporal heterogeneity produce further imbalances between supply and demand. This means that part of a catchment can remain in a state of water surplus while another part of the same catchment can experience water shortage. Collapsing this fine-grained nature of hydrological regimes into a single freshwater PB makes us prey to the averaging fallacy and blind to the key role of local conditions in determining how much water is available and how it should be used (Molden 2009).

The GCEW's planetary annual scale is therefore a closed and simple unitary system. Strictly speaking, at this scale there is no local heterogeneity that gives rise to water shortfalls or 'crises'. As GCEW's own Figure 1 (above) shows, planetary-level hydrology is defined by the neat division of an annual rainfall amount into different sectors. While the law of conservation of mass is upheld at this scale (Perry et al., 2023), it is the very lack of conservation of water mass and compensatory transfers across time and space that generates 'crises'. In that regard, Figure 1 fails to present four important hydrological features that help explain water crises:

- Readers are presented with average hydrological figures for the whole planet without discriminating between uninhabited, oceanic, temperate, desert, mountainous or polar regions (Nordhaus et al., 2012).

- There is no consideration of spatially variegated, intra-sector, increasing, nested or wealth-influenced societal demands that give rise to local and cumulative water stresses.
- There is an evening out of the monthly and/or seasonal variations in supply and demand that govern many 'crises'.
- There is a failure to include time- and volume-dependent flows of precipitation, streamflow and phreatic water mediated by catchment soils and geology.

The GCEW reports would have benefited from explaining to the reader that concerns over water scarcity are found principally in river basins in subtemperate, subtropical and tropical regions where: 1) water sharing is significantly shaped by withdrawals and consumption of very high volumes of water by irrigation; and 2) monsoonal and semi-arid rainfall patterns bring uncertain amounts, timings and locations of rainfall and runoff. Such a place-based view of water could have allowed the GCEW to build up a globally significant but disaggregated picture of water scarcity by drawing only on these highly populated, geopolitically tense, and increasingly urbanised regions (Fernando, 2023).

As discussed by Heistermann (2017: 3457), the fact that the original freshwater PB obliterated the heterogeneities existing at the regional level was acknowledged by the proponents of the PB concept, who in ulterior works tried to identify basin-level boundaries and figure out how water stress at the regional level can feed up to the planetary scale (Gerten et al., 2013; Steffen et al., 2015). This expansion of the PB framework, however, raises more questions than it answers. First of all, empirical evidence for mechanisms leading to the collapse of the water system seem to be as feeble at the local level as they are at the global level. Second, it is unclear why we need a global freshwater PB framework if there is a possibility of pinpointing regional thresholds that would allow policymakers to take more tailored and directed action. And finally, if freshwater use is a PB with "strong regional operating scales" – as argued by Rockström in the discussion found in Heistermann (2017) – and if there are "basin-scale boundaries for maximum blue water withdrawal along rivers" – as argued by Steffen et al. (2015: 7) – then surely the GCEW report would have benefited from discussing how these regional thresholds, which must vary significantly, give rise to a precise freshwater PB.

A planetary-scale frame fails to support policy formulation

It is unclear how we can derive tailored policy recommendations from a so-called 'global water crisis' narrative if, as acknowledged by the proponents of the PB framework, many water imbalances happen at the local/regional level. Should not a place-based focus be able to better address water challenges? If the crisis in a significant majority of the world's river basins is one of over-consumption by irrigation, then a picture of per-basin sectoral imbalances can be established, followed by the suggesting of potential water-reallocation policies. Alternatively, one could also begin with policy views about solutions to the global water crisis to inform how best to analyse and present the crisis (van Vuuren et al., 2016). If, for example, groundwater and artificial water storage are to be the globally significant future solutions to the water crisis, then the latter should be identified as relevant in places where supply and demand are affected by wet and dry periods.

The planetary focus of the GCEW engenders the following challenges in shaping policy:

- Few of the policies have their origins in a PB view of managing global water. The main report, for example, states that economic and market solutions are its priority (GCEW, 2023: 40), yet there is no analysis of how markets will bring the necessary changes that will manage the global water cycle at the planetary scale.
- By referring to changes in global vapour flows as evidence of the global water crisis, Rockström et al. (2023b: 796) suggest managing the global water cycle directly. Practically and policy-wise, however, this makes little sense as there are no conceivable tools for managing atmospheric

vapour (Venot, 2023; Barbier, 2023; see also the 'Dissensus Forum' discussion at www.water-alternatives.org/index.php/blog/tide).

- The reports' planetary-level focus means that the GCEW does not expend effort in carefully unpacking policy instruments to redress imbalanced blue water consumption. As a result, the GCEW is de facto placing new faith in economics and markets to regulate water demand, effectively rerunning the 1992 Dublin Principles which promoted rather discredited market-based experiments (Molle and Berkoff, 2007).

Poor definition of the global blue and green water crisis

It is unclear whether the GCEW (2023) treats blue and green water as a single water limit or as separate limits. Some parts seem to favour the second interpretation, as evidenced by, for example, "the global water cycle must remain within a manageable range for both green and blue water available limits" (GCEW, 2023: 10), "all water boundaries (i.e. blue and green water)" (ibid: 13), or "we have crossed both the blue water consumption boundary and the green water boundary" (ibid: 19).

The GCEW (2023: 10), however, merges the two types of water into a lower limit of 1200 m^3/yr/person and nowhere in their main report is the green water and its limit defined and specified. Instead, it is seen either as soil moisture (ibid: 8), land-use change (see next paragraph), evapotranspiration, global vapour flow, green-water flux (ibid: 58) or a personal budget that includes embedded crop water requirements (ibid: 10). The confusion peaks in the following sentence (ibid: 58): "The excess availability of blue water via flooding or green water via evapotranspiration at the cost of scarce blue water is problematic from the local to the global".

Elsewhere (GCEW, 2023: 13) the reader is told that, "the green water planetary boundary may already have been transgressed (Wang-Erlandsson et al., 2022: 380)", without being provided with any information about the nature of the limit and why it has been crossed. This backgrounding tactic allows the GCEW to state something as a matter of fact that is far from certain. By measuring the green water PB based on proxy land-use changes compared to pre-industrial eras, the Wang-Erlandsson paper reveals that land-use impacts on soil water content have varied from the long-term mean. Importantly, however, these results are not corroborated by other methods of measuring green water or by defining green water by volume. If anything, Wang-Erlandsson et al. show that how we judge recent land-use change, while significant, is nonetheless arbitrary. We speculate that the GCEW report opted not to define a green water boundary in terms of water volume (km^3) per annum because such a metric does not currently exist, nor do clear procedures for gathering such data.

With regards to blue water, there appears to be some ambiguity in the defining of consumptive and non-consumptive water use. If water use is mainly non-consumptive, then its withdrawal does not deplete basin-scale volumes. The title of Figure 1 uses the word consumption twice, but in the figure three grey arrows join to show water returning to the ocean. The diagram's arrows are saying that some of irrigated agriculture water use and all of industry and urban water use is non-consumptive (otherwise all three sectors would have green arrows to evapotranspiration). In Figure 1, the GCEW also states that human consumptive use amounts to 1600+400+350 = 2350 km^3/yr. However, if we accept the arrow colour coding, these figures are 'water withdrawals' (containing both green arrow consumptive use and grey arrow non-consumptive use). If this were the case, water consumption by all three sectors would be a fraction of the withdrawal figure of 2350 km^3/yr.

The poor diligence of the GCEW in defining the blue and green water crisis is matched by its use of a confusing array of terms for the global water crisis. These include "world water crisis", "water scarcity", "global water crisis", "water crises" (GCEW, 2023: 21), "water and planetary boundaries" (ibid: 39), and "planetary boundaries for water" (ibid: 10). Several terms which imply metrics are also ill-defined, such as "upper boundaries of water use" (ibid: 10), "water use patterns" (ibid: 10), "blue water consumption exceedance" (ibid: 10), "global blue water limit exceedance" (ibid: 10), "freshwater supply" (ibid: 11), "water requirements" (ibid: 11), "human impacts on the water cycle" (ibid: 12), "global blue consumption limit" (ibid: 19), "blue-water limit exceedance" (ibid: 19), "crossing water (use) boundaries" (ibid: 21), "global water consumption" (ibid: 22), "global water withdrawals" (ibid: 22), and "water limits" (ibid: 53). This ambiguity weakens the GCEW's emphasis on the importance of accurate water accounting that is found in the main report (ibid: 11) and elsewhere in supporting reports (Perry et al., 2023; Vardon et al., 2023).

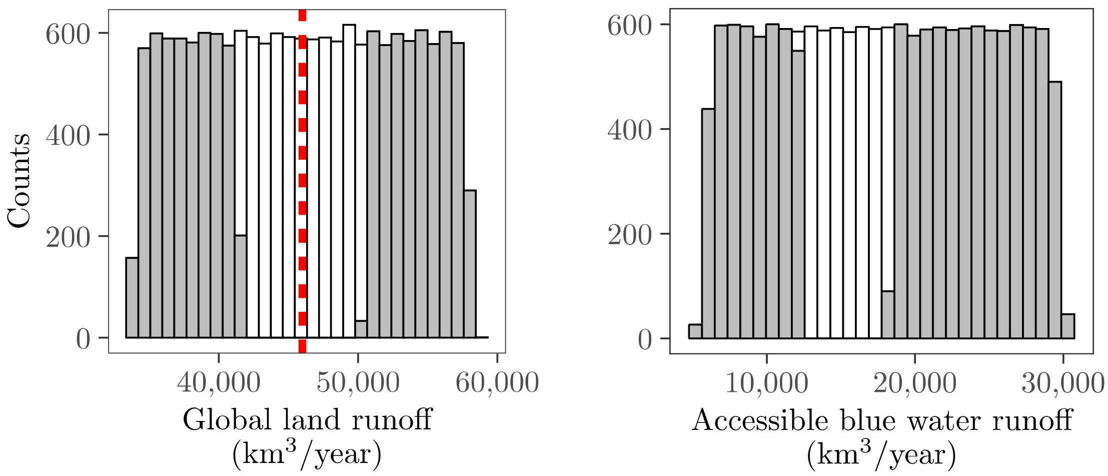
THE INNUMERACY OF GCEW'S APPROACH TO QUANTIFICATION

In the previous sections we have discussed the framing of the GCEW global water crisis narrative. Here we examine the numbers underpinning it. Since no GCEW report explicitly presents the calculations used by the authors to quantify their 'safe space', we had to reverse engineer their approach to obtain the relevant equations (Annex, Equations 4-6). As we show below, the GCEW's quantification suffers from faulty arithmetics, uncertainty neglect, and selective data picking.

Incorrect human impact calculations

Let us first focus on Figure 1, which shows the impact of human water use on global land runoff and the volume of accessible blue water runoff. The GCEW quantifies global land runoff at 46,000 $\pm$ 10% km^3/yr (that is, 41,400 to 50,600 km^3/yr). Upon closer inspection of the numbers in Figure 1, however, it becomes evident that the range should be 33,400 to 58,600 km^3/yr. We provide the proof of this miscalculation in the Annex (Section 6.1). Such artificial narrowing of the uncertainty cascades into the calculation of accessible blue water runoff, which should be 5245 to 30,354 km^3/yr, not 12,500 to 18,500 km^3/yr. Figure 1 thus excludes a substantial portion of the data pertaining to the ranges that the GCEW has used to define global land runoff and accessible blue water runoff (see Figure 2).

Figure 2. Number auditing and Monte-Carlo based uncertainty analysis.



Note: The white portion of the histograms represents the values in Figure 1, while the grey portion indicates the range of the distribution when the arithmetic mistakes in the calculation of global land runoff are corrected and the calculation is conducted in a Monte-Carlo setting. The red dashed line represents the point estimate of 46,000 km^3/yr for global land runoff used in the GCEW report.

The calculation of accessible blue water runoff is crucial as it is the baseline for assessing human pressure on freshwater resources. If a significant portion of accessible blue water is consumed by agriculture, industry and urban areas, the notion of an imminent water crisis receives empirical support. Figure 1 indicates that human water usage amounts to 2350 km^3/yr, with 1600 km^3/yr being consumed by agriculture, 400 km^3/yr by industry, and 350 km^3/yr by urban areas. However, with the corrected ranges for accessible blue water runoff, 2350 km^3/yr amounts to just 5 to 45% of all freshwater resources, with irrigation having the most substantial impact (5 to 30%) (Annex, Figure S1a). Rather than providing evidence of a crisis leading to an unsafe operating space, the numbers managed by the GCEW indicate that humans have, on average, a relatively low consumptive impact on accessible blue water runoff.

The calculation of the 'blue water limit exceedance' for 2023 and 2050

Let us now explore the numbers produced by the GCEW to illustrate by how much we have surpassed the 'safe space' for water. According to the GCEW, in 2023 we already exceeded the global blue water limit by 161 to 414 km^3/yr and in 2050 we will exceed it by 501 to 754 km^3/yr (Table 1).

Table 1. Global blue water limit exceedance according to the GCEW.

Year	Range	Unit
1950	0	km^3/yr
2023	161 – 414	km^3/yr
2050	501 – 754	km^3/yr

Source: GCEW (2023).

Note: See also the orange table in Figure 1.

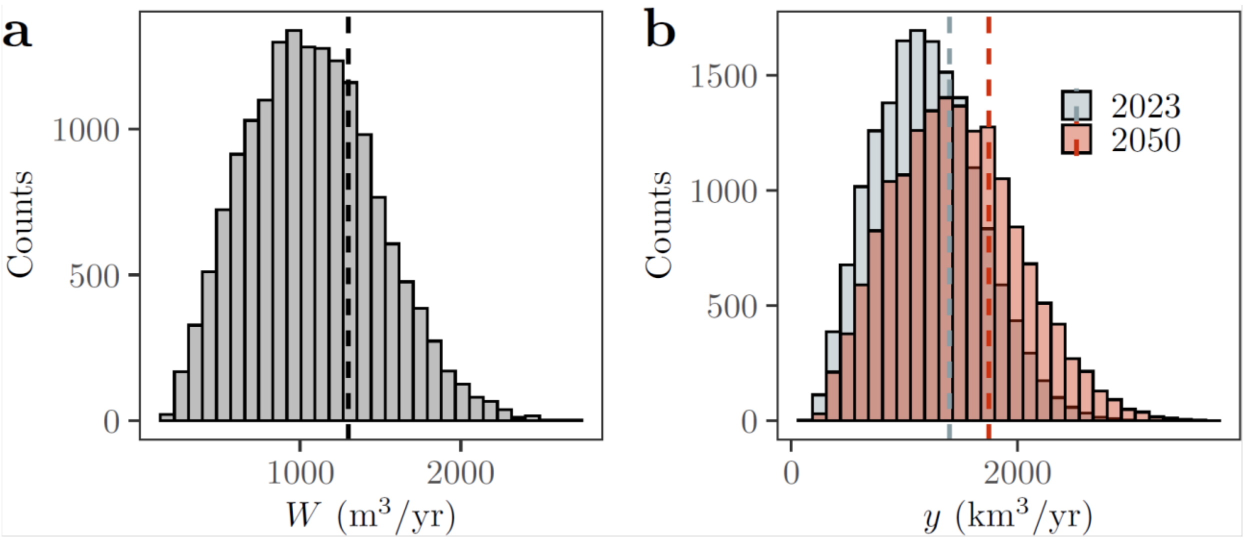
GCEW took the following steps to produce the numbers in Table 1:

1. Calculation of lower and upper limits of 'blue water exceedance' in 2023 based on, among other parameters, groundwater and irrigation consumption (the steps taken by the GCEW in the calculation of this 'blue water exceedance' are detailed in the Annex).
2. Estimation of the amount of green + blue water required per person to sustain a 3000 kcal/day diet. The GCEW sets this value at 1300 m^3/yr following a model by Rockström et al. (2005: 15-16).
3. Calculation of global water consumption per year: the GCEW calculates this figure by plugging the 1300 m^3/yr figure mentioned above into a model that also requires data on population and on the ratio between green and blue water (see Annex, Equation 5). Global water consumption thus gets estimated at 1400 km^3/yr for 2023 and at 1750 km^3/yr for 2050; 1400 is then subtracted from 1750 to obtain 340 km^3/yr, the 'water limit excess' expected by 2050. This figure finally gets added to the lower and upper estimates for blue limit exceedance in 2023 to produce the ranges for 2050 (Table 1).

In the Annex, we show that this chain of calculations rests on at least nine highly sensitive assumptions that are characterised by, among other things, feeble empirical support, deceitful cross-checks, lack of grounding in real-world data, and disregard for uncertainties (for example, transformation of ranges and distributions into sharp numbers). To explore the extent to which the GCEW ranges proposed in Table 1 are robust against changes in the assumptions underpinning their models, we submitted the calculation of the amount of water required per person and the global water consumption per year (Equations 5 and 6 in the Annex) to a variance-based uncertainty and sensitivity analysis (UA/SA) (Puy et al., 2022a; Saltelli et al., 2008).

The results indicate that, once basic uncertainties are propagated in the calculation, the amount of green + blue water required per person to sustain a given diet no longer equals 1300 m^3/yr. Instead, it follows a Weibull distribution that ranges from 150 m^3/yr to 2700 m^3/yr, with the median being 1050 m^3/yr (Figure 3a). As for the global water consumption per year, the estimations by the GCEW (1400 km^3/yr in 2023 and 1750 km^3/yr in 2050) turn into ranges spanning more than one order of magnitude (180 to 3100 km^3/yr in 2023, 220 to 3800 km^3/yr in 2050) (Figure 3b). These wider ranges throw doubt upon predictions of a looming water crisis due to humans having crossed freshwater planetary boundaries.

Figure 3. Projection of global water consumption to 2050: a) distribution of the estimated amount of water required per person to sustain a given daily diet (W) once uncertainties are propagated in the calculation; b) distribution of global water consumption in 2023 and 2050 (y) once uncertainties are accounted for in the calculation.



Note: The dashed, vertical line in Figure 3a shows the value used by the GCEW (1300 m^3/yr); the dashed, vertical lines in Figure 3b show the values used by the GCEW for 2023 and 2050 (1400 and 1750 km^3/yr) (see the Annex for more details).

Regarding sensitivities, the parameter with the highest impact on the calculation of global water consumption is the water requirement for producing 1000 kcal of vegetables, which is ingrained in the estimation of the amount of water required per person (Annex, Table S2). This parameter contributes approximately 40% of the overall uncertainty, whereas the rest of the parameters involved in the calculation contribute about 20% of the uncertainty in the output. Notably, 15% of the total uncertainty in the estimation is attributed to interaction effects, indicating the non-additive nature of the model. The output uncertainty is thus shaped by intricate interdependencies among the model components, rather than being a simple summation of individual uncertainties (Figure S1f). This means that the uncertainty in the estimation of global water consumption may not be easily reduced even if we were able to significantly minimise the uncertainty in each one of the model parameters.

It is important to clarify that the analysis above does not aim to replace GCEW's figures with the 'true' global water consumption or the 'true' individual water requirement ranges. It is beyond the scope of this paper to discuss whether defining these ranges is scientifically feasible or whether it involves entering the domain of trans-science (where questions are posed in scientific language but cannot be answered by science; see Weinberg, 1972). Our goal with this specific exercise is to show that, without engaging in a formal debate on the appropriateness of the modelling framework selected by the GCEW, its inferences do not withstand scrutiny and fail even within their established PB framework.

Finally, we note that the GCEW calculations draw on papers that have undergone peer review and are therefore part of the scientific body of knowledge. The GCEW's estimation of the volume of water required per person to sustain a 3000 kcal/day diet (Annex, Equation 6), for instance, draws from a model by Rockström et al. (2005: 15-16) that was published 20 years ago. Note that this is not a model of a physical, context-free, universal process: rather, it establishes normative standards for what, in the real world, is a decision resulting from a complex amalgamation of fluctuating, ethically charged, and socially influenced decisions regarding food choices and consumption amounts (Annex, Section 6.3). There is no reason to think that the assumptions upon which this model rests cannot be changed to incorporate other ethical stances and values (e.g.; a different caloric target based on a different balance of meat and vegetables). This is exactly the problem with this sort of models: unless publication has been preceded by a systematic exploration of its uncertainty space, vetting by the academic community is no guarantee that the model-based estimates are robust enough to act as a foundation for future works. In other words, models that are fragile against uncertainty may not be the most appropriate tools in a context of 'normal science' pursuing cumulative knowledge. The GCEW seems to have largely constructed their narrative on past work that corroborated their hypothesis, without expecting that someone would assume the burden of reading past all this literature in an adversarial assumption-hunting mode. It is thus worth recalling one tenet of sensitivity auditing: conduct your sensitivity analysis before publishing and "find sensitive assumptions before they find you" (Saltelli et al., 2013).

DISCUSSION AND CONCLUSIONS

In this paper, we present evidence that the GCEW's water crisis narrative is totalising: it flattens water's nestedness and heterogeneity into one planetary scale, fails to accommodate alternative ways of seeing the global water crisis, and is not supported by rigorous science. It is not only that the adoption of the planetary boundaries (PB) framework to make sense of the water crisis may be deemed questionable considering the available evidence: it is also that, even if we grant it appropriateness, the numbers underpinning it result from neglecting uncertainties, cherry-picking data, and omitting contradictory or alternative information. Similar research practices are documented in psychology or in ecology and evolution research (Fraser et al., 2018). Such practices are one of the causes of the so-called "replication crisis" in science, that is, the proliferation of studies with inflated, manipulated or false results that cannot be replicated and thus lead to loss of public trust in science (Saltelli and Funtowicz, 2017). To our knowledge, the extent to which water-related studies or reports suffer from these biases has not been explored and therefore the GCEW's reports may not be representative of the trends in hydrology and water modelling. However, the willingness of water modellers and institutions to inform thinking and action in the real world, combined with the characteristic flexibility of hydrological models (whose degrees of freedom permit modellers to pre-specify the answer to a given problem specification) (Konikow and Bredehoeft, 1992), create favourable conditions for such habits to develop.

Our analysis also suggests that the GCEW reporting has downplayed information regarding the assumptions and structure of the models that underpin their water crisis narrative. This backgrounding of key material hinders criticism and imposes a significant burden on readers who wish to critically assess the strength of the evidence supporting the GCEW's claims, as it compels them to mine past literature (Huckin, 2002; Blommaert and Bulcaen, 2000). Indeed, when a model designed to enact a specific scientific narrative (such as the PB framework) becomes institutionalised, all the assumptions, abstractions, idealisations, ethical stances, value-ladenness and worldviews ingrained in its design are forgotten and become invisible. The more papers added to that dominant body of literature, the more difficult it is to unearth its key tenets. Its embedded worldviews get buried beneath conforming literature, creating the illusion that the model is a neutral simulation devoid of personal bias. Its produced inferences are then taken up without much question, with efforts directed more towards refining its produced numbers rather than digging them up to have a peek inside the particularities of the model's black box.

Any model-based study of the water cycle that is aimed at informing policy-making should prioritise transparency and come to terms with uncertainties. This obligation arises not only from the uncertainty characterising various parameters and assumptions in water models, but also from the fundamental limitations of hydrological models in their representation of real-world water processes (Puy et al., 2023; Konikow and Bredehoeft, 1992; Oreskes et al., 1994). Unless we embrace a contentious metaphysical realism and assume an all-knowing perspective (that we can describe the world 'as it truly is'), we should consider that models are incomplete, historically situated representations of specific phenomena and that they are influenced by the assumptions, interests, value judgments and disciplinary viewpoints of their creators (Saltelli et al., 2020; see Melsen, 2022 for hydrological models). At each step of a model-based exercise, from problem formulation to data acquisition, several equally legitimate alternative choices are available to the researcher – choices that end up determining the final model output. This is often referred to as the "garden of forking paths" (Borges, 1941) or the issue of the researcher's degrees of freedom (Breznau et al., 2022). A single model with no previous uncertainty and sensitivity analysis (UA/SA) results from collapsing countless possible paths into one; its output does not mirror an 'objective' reality as much as the consequences of choosing a single track from the many that are available.

The GCEW's failure to consider uncertainties in calculations and account for the limitations of the PB framework, coupled with alarmist statements such as the assertion that the global water crisis will "spare no person, place, economy, or ecosystem if left unaddressed" (GCEW, 2023: 6), prompts several concerns about the GCEW's real goals.

First, there is a failure to provide a balanced overview of all potential courses of action given our best available water science. This shifts the emphasis to a specific global political and economic project using the transgression of the planetary boundaries as a scientific justification. If the planetary boundaries are an empirical, already-breached limit, then there is not much space for political negotiation: society just needs to be told what these boundaries for water are, sanction the creation of an overarching regulatory institution that makes sure they are not transgressed again, and accept the required measures to get back to a 'safe space' (Pielke Jr, 2023). Indeed, advocates of the planetary boundaries framework have been requesting the creation of such a supra-national organisation for quite some time. Almost 15 years ago, for example, Steffen et al. (2011: 5) argued that we need "an institution (or institutions) operating, with authority, above the level of individual countries to ensure that the planetary boundaries are respected". Recently, Rockström et al. (2024) took a step further by dedicating a full paper to sketching what features this overarching institution should have if it is to safeguard the 'planetary commons'. Given its scientific orientation, it is evident that this planetary commission would be better refereed by experts in the PB framework than by politicians who are democratically elected but lack scientific credentials. With the GCEW reports, the notion of a supra-national governmental body, in which advocates of planetary boundaries have the final say, garners additional support through its endorsement by an institution directly linked to the policy realm. It is worth recalling that the GCEW is convened by the Government of the Netherlands and the OECD, and includes presidents, ministers of foreign affairs and mayors as co-chairs and commissioners. This makes the GCEW resemble not so much a science-based commission as a commission formed by policymakers employing preselected 'scientific evidence' to advance their specific interests.

Second, and in relation to these 'interests', the GCEW's narrative reifies a planetary boundaries economic approach to water. In other words, it flattens the terrain for the establishment of new worldwide standardised policies, even if they belong to the worn-out catalogue of panaceas (Meinzen-Dick, 2007; Mukhtarov, 2022). This is precisely what seems to be happening, with a policy framing in which water is economically valued and managed via global markets and pricing despite the manifest difficulties of implementing neoliberal and market-oriented blueprints (Molle and Berkoff, 2007). Economic policies based on a planetary boundaries framework are likely to remove or delegitimise solutions arising within local-to-basin scales in responding to future interventions. Irrigation, for instance, has at least five scales of socio-technical influence: field, secondary unit, tertiary unit, main system and basin (Lankford et al., 2020; Uhlenbrook et al., 2022; van Oel et al., 2019). In certain circumstances and specifically at lower scales, relying on market-based, or water accounting, virtual water, footprinting and offsetting approaches to water management is likely to be inefficient and unsuitable (Lankford, 2022; Wichelns, 2015).

The worldwide existence of significant water challenges is undeniable. Water's underpinning to food, environmental and economic resilience, and security (Ringler et al., 2022) is a subject of growing concern due to competition over increasingly scarce freshwater resources, and this is likely to intensify in the coming decades due to climate change (Matthews et al., 2022). There is little doubt that water should be placed high on the political agenda (Irannezhad et al., 2022; Biswas, 2019). However, our capacity to properly discuss ways forward is undermined when poor science combines with prophecies of disaster uttered by organisations with a very wide reach. In the climate change arena, unfulfilled predictions of catastrophic outcomes have served to fuel climate denialists and anti-science advocates while contributing to the spread of climate anxiety, especially among young people (Hulme, 2023). The GCEW's use of the planetary boundaries framework may contribute to this effect if it is presented as a real, literal, empirically grounded threshold rather than as a 'space-ship Earth' metaphor (Sax, 1990) that help us think about the limits of our environment.

The urgency to address current water problems should not make us forget that water is a multifaceted issue. The effects of water scarcity on humans and the environment do not depend exclusively on physical processes prone to be described by mathematical models: they are also determined by political negotiations, social structures, professional norms, and individual and collective perceptions as to what water is and how best to use it. In other words, there are many water-affecting processes that escape formalisation. Turning our backs on this complexity in favour of numericised, model-based evidence without a proper assessment of uncertainties leads to spuriously precise outputs with no clear connection to anything real (Puy et al., 2022b; Puy et al., 2023). More importantly, as we see with the GCEW enterprise, such oversimplification artificially forecloses the range of possible policy initiatives and futures available to us.

If water's known complexity and ambiguity is embraced, scientific analysis does not usually lead to a unique single-scale policy answer. Definitive science-based decisions are, in these circumstances, a contradiction in terms (Stirling, 2010). Under these scenarios, the value of scientific research lies more in its capacity for promoting organised scepticism and opening up the range of evidence rather than in fostering an artificially narrow discourse that forecloses debate. Embracing a clarity of ideas and definitions, awareness of plural scales and viewpoints and ambiguity in quantitative analysis permits invitation and negotiation. It makes explicit the conditionality of model-based inferences and sheds light on the different stakes involved in the problem. The result is a more plural and more democratically accountable policy process with greater potential to reach a robust, durable outcome. Examples of this wider, multidisciplinary and deliberative approach are found in the Comprehensive Assessment of Water Management in Agriculture (CAWMA, 2007) and the World Commission on Dams (2000). The GCEW seems to have taken an opposing pathway.

ANNEX

Incorrect human impact calculations

The GCEW arrives at the figure of 46,000 $\pm$ 10% km^3/yr (41,400 – 50,600 km^3/yr) for global land runoff G_r as follows:

$$G_r = P - ET, \tag{1}$$

where P is precipitation and ET denotes the evapotranspiration resulting from natural vegetation V and rainfed crops R. Note that the GCEW describes these two parameters with ranges, as $V = [V_1, V_2] = [68{,}200, 68{,}800]$ and $R = [R_1, R_2] = [5{,}200, 5{,}800]$. Since $P = [P_1, P_2] = [108{,}000, 132{,}000]$, then

$$ET = [V_1 + R_1, V_2 + R_2] = [68{,}200 + 5{,}200, 68{,}800 + 5{,}800] = [73{,}400, 74{,}600], \quad (2)$$

and in consequence,

$$G_r = [P_1 - ET_2, P_2 - ET_1] = [108{,}000 - 74{,}600, 132{,}000 - 73{,}400] = [33{,}400, 58{,}600]. \quad (3)$$

The calculation of the blue water limit exceedance for 2023

The GCEW calculates the lower and upper boundaries for global blue water limit exceedance in 2023 as follows:

$$y = W_g + F_i W_s F_u \quad (4)$$

where y represents the lower/upper limit of blue water exceedance in 2023 in km^3/yr. The other parameters and the values used by the GCEW to characterise them are listed in Table S1**.**

Table S1. Parameters used by the GCEW in the estimation of lower and upper boundaries for global blue water limit exceedance.

Parameter	Description	Unit	Value	Justification
W_g	Lower/upper estimate for groundwater consumption	km^3/yr	84/304	Scanlon et al. (2023)/ Wada and Bierkens (2014: 6)
W_s	Lower/upper estimate for irrigation consumption	km^3/yr	1083/1550	Rosa et al. (2020)/ Molden (2007: 6)
F_i	Fraction of irrigation over total water consumption	[-]	0.71	Döll et al. (2014, Table 2)
F_u	Fraction of unsustainable irrigation	[-]	0.1	-

Thus, using Equation 4, the GCEW produces a lower estimate of approximately 161 km^3/yr (84 + 0.71 × 1083 × 0.1) and an upper estimate of 414 km^3/yr (304 + 0.71 × 1550 × 0.1) (Table 1).

We observe four problems with this calculation:

- Incorrect and/or dead-end citations. We did not find the values of 84 km^3/yr and 1550 km^3/yr in Scanlon et al. (2023) or in Molden (2007: 6) respectively. In fact, the latter appears to discuss withdrawals instead of consumption, suggesting a value of 2700 km^3/yr. Citations of sources that do not contain the attributed statement do not lead anywhere and are known in the literature as 'dead-end citations' (Greenberg, 2011).
- Feeble empirical support. Only one study suggests that 71% of the water globally used in irrigation is surface water (F_i = 0.71) (Döll et al., 2014, Table 2). Other studies suggest other figures: Siebert et al. (2010: 1863), for instance, propose 57%. In any case, local/national variability is as large as to question the significance and policy utility of a single global estimate: according to the Supplementary File in Siebert et al. (2010), 52 countries out of the 205 examined use >95% surface water (i.e. Venezuela, Vietnam, Indonesia), 17 countries use <20%, and 12 countries use <5% (Oman, Saudi Arabia, United Arab Emirates) (Figure S1b).
- The report also lacks justification for assuming 10% as the unsustainable portion of all surface water consumption in irrigation (F_u = 0.1). Although they focus on withdrawals, Pastor et al. (2022) suggest a deficit of 16%-34% (F_u = [0.16-0.34]).

Deceitful cross-check. The report 'validates' the water limit exceedance of 161–414 km^3/yr in Table 2 by referencing other estimates that allegedly fall into this range, such as 273 km^3/yr (Rosa et al., 2020) or

370 km^3/yr (Jaramillo and Destouni, 2015: 1249, 1250). The GCEW derive the latter by subtracting 4370 km^3/yr (claimed to be Jaramillo and Destouni's estimation of total global human freshwater consumption) from 4000 km^3/yr, the freshwater PB proposed by Steffen et al. (2015).

However, the GCEW selected 4370 km^3/yr and 4,000 km^3/yr without considering their uncertainty. Jaramillo and Destouni's estimate (2015) is actually 4370 ± 979 km^3/yr, equivalent to a range of 3391 – 5349 km^3/yr. Additionally, the freshwater PB of Steffen et al. (2015) has an uncertainty range of 4000-6000 km^3/yr. By subtracting these ranges, the resulting distribution does not offer clear evidence of a water overshoot: in fact, there may be a considerable water surplus (up to ∼2000 km^3/yr, Figure S1c-d).

The calculation of the blue water limit exceedance for 2050

Let us now explore the derivation of a water exceedance range of 501-754 km^3/yr for 2050 (Table 1). The calculations by the GCEW involve some coarse rounding up. The basic model calculates the global water consumption per year [km^3/yr] (y) and reads as

$$y = PF_bW, \tag{5}$$

where W is the estimated water required per person to sustain a 3000 kcal/day diet and, according to Rockström et al. (2005: 15-16),

$$W = \frac{365\left(kF_mF_{m_w} + kF_vF_{v_w}\right)}{1000}, \tag{6}$$

Table S2 details the parameters and values used by the GCEW to solve Equation 6, which yields W ≈ 1300 m^3/yr and hence y = 1400 km^3/yr (8 × 0.1346154 × 1,300) for 2023 and y ≈ 1750 km^3/yr (9.7 × 0.1346154 × 1300 and rounding up to 1750 from 1698) for 2050. By subtracting 1400 from 1750 we obtain 340 km^3/yr, used by the GCEW as the water limit excess by 2050.

Table S2: Parameters used by GCEW in the estimation of water exceedance in 2050.

Parameter	Description	Unit	Value	Justification
P	Population size	10^9	8 (2023), 9.7 (2025)	[-]
F_b	Green/blue water ratio	[-]	0.1346154	[-]
k	Kilocalories per capita per day	kcal	3000	Rockström et al. (2005: 15-16)
F_m	Diet fraction based on meat	[-]	0.2	Rockström et al. (2005: 15-16)
F_v	Dietfraction based on vegetables	[-]	0.8	Rockström et al. (2005: 15-16)
F_{m_w}	Water to produce 1000 kcal of meat	m^3	4	Rockström et al. (2005: 15-16)
F_{v_w}	Water to produce 1000 kcal of vegetables	m^3	0.5	Rockström et al. (2005: 15-16)

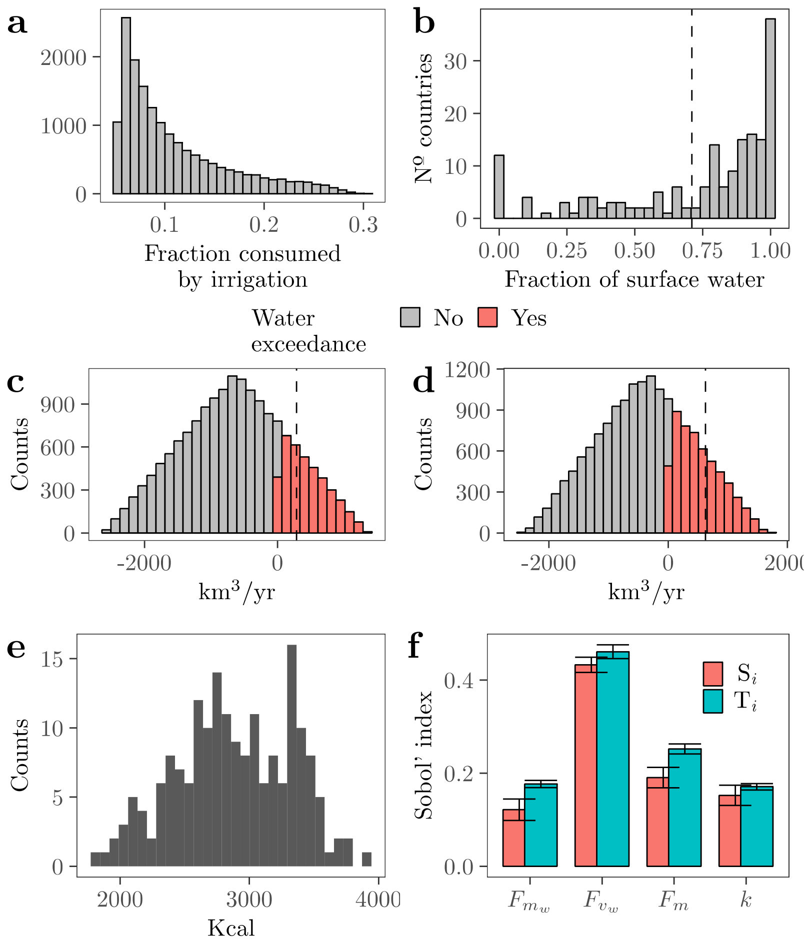
Finally, by adding this excess of 340 km^3/yr to the lower and upper estimates for blue water limit exceedance in 2023 (161 and 414 km^3/yr, respectively), the GCEW obtains the range of 501-754 km^3/yr for blue water limit exceedance in 2050 (Table 1).

We note the following six issues with this calculation:

1. Lack of foundations. The calculation of the blue water limit exceedance for 2050 plugs in the 2023 numbers, whose shaky nature we have discussed in the previous section.

2. The 3000 kcal/day figure is not grounded in real-world data. It is the desired caloric consumption intake projected by the FAO for developing countries in 2030 to fully eradicate undernourishment. It does not reflect current caloric consumption patterns, which show a large variability (Fig. S1e). In North America it approaches 3700 kilocalories per capita per day, whereas in many African countries it falls below 2500 kilocalories (Gerten et al., 2011). By applying Equation 6 to estimate water requirements per capita in 2023, the GCEW uses a future policy ideal into a de facto state-of-affairs, and assumes that current water consumption patterns already guarantee a minimum dietary intake for everybody. This premise is untenable and compounds the already questionable assumption that water consumption in 20 years will be that of a world without undernourished individuals.
3. Fixed percentage of meat in the diet. The fraction of the diet based on meat, as used in Equation 6, is set at F_m = 0.2 according to Rockström et al. (2005). However, the FAO states that whereas an European or North American diet includes c. 35% of meat, several countries in Africa and Asia predominantly follow a vegetarian diet, with meat comprising only 1-15% of their dietary intake (Gleick, 2000). Setting F_m = 0.2 implies that a significant portion of the world consumes approximately 10 times more meat than it does, and that this figure will extend into at least 2050.
4. Hidden internal variability. Although Equation 6 yields W ≈ 1300 km^3/yr, the requirements to achieve a balanced diet consisting of 3000 kilocalories per capita per day vary greatly: countries in Europe may be better described by W < 1000 km^3/yr, while countries in Africa by W > 2500 km^3/yr (Gerten et al., 2011).
5. Unjustified water figures for 1000 kcal of meat and vegetables. We found no justification for the choices of F_{m_w} = 4 and F_{v_w} = 0.5 made by Rockström et al. (2005) and Falkenmark and Rockström (2004). The Institution of Mechanical Engineers (IME, 2013) notes that producing 1 kg of meat requires between 4300 (chicken) and 15,500 (beef) litres of water. With meat providing around 4 kcal per gram, 1000 kcal of meat would require 1 to 4 litres of water. By setting F_{m_w} = 4, the GCEW assumes the highest water consumption, implying that all produced meat is the most water-intensive, namely beef. As for the water volume required to produce 1 kg of vegetal food, a diet based on vegetables, fruits, cereals and pulses requires between 300 (vegetables) to 4000 (pulses) litres, which provide between 0.3 (vegetables) to 3.4 (pulses) kcal per gram (Mekonnen and Hoekstra, 2010: 29). This implies that 1000 kcal of vegetal products will necessitate between 0.16 to 1.25 cubic meters of water. This range is obscured by the GCEW following Rockström et al.'s (2005) proposed value of F_{v_w} = 0.5.
6. Need for an eight-digit precision. The parameter F_b (ratio between green and blue water consumption) has to be 0.1346154 in Equation 5 to fully reproduce the values yielded by the GCEW. The need for a highly accurate constant resulting from the ratio between two uncertain estimations is implausible. Note that the GCEW assumes that this constant will remain fixed at eight-digit precision over 30 years.

Figure S1. Uncertainty and sensitivity analysis.



a) Fraction of accessible blue water runoff consumed by irrigation. b) Distribution of the fraction of blue surface water used in irrigation per country after Siebert et al. (2010). The black vertical dashed line shows the estimate used by GCEW to calculate water exceedance rates (0.71) (see Table S2). c) Uncertainty in water limit exceedance when assuming a threshold of 4000 – 6000 km^3/yr (Steffen et al., 2015) and a total global human freshwater consumption of 4370 ± 979 km^3/yr (Jaramillo and Destouni, 2015). d) Uncertainty in water limit exceedance for the 2050 calculation. e) Country-level distribution of daily caloric intake. Data are based on FAO and on historical sources and was retrieved from Our World in Data (*https://ourworldindata.org/calorie-supply-sources*). f) Sobol'-based sensitivity analysis (SA) of Equations 5-6 for 2023. The red bars show the first-order effect (S_i), i.e.; the proportion of variance conveyed by a given parameter to the model output. The blue bars display the total-order effect (T_i), i.e.; the proportion of variance conveyed to the model output by a given parameter plus all its interactions with the rest. When $S_i < T_i$, the parameter is involved in interactions.

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The code to reproduce our results is available in Zenodo (Puy, 2024). All data needed to evaluate the conclusions in the paper are present in the paper, the Annex and the code.

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