Article

Living within the safe and just Earth system boundaries for blue water

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Safe and just Earth system boundaries (ESBs) for surface water and groundwater (blue water) have been defined for sustainable water management in the Anthropocene. Here we assessed whether minimum human needs could be met with surface water from within individual river basins alone and, where this is not possible, quantified how much groundwater would be required. Approximately 2.6 billion people live in river basins where groundwater is needed because they are already outside the surface water ESB or have insufficient surface water to meet human needs and the ESB. Approximately 1.4 billion people live in river basins where demand-side transformations would be required as they either exceed the surface water ESB or face a decline in groundwater recharge and cannot meet minimum needs within the ESB. A further 1.5 billion people live in river basins outside the ESB, with insufficient surface water to meet minimum needs, requiring both supply- and demand-side transformations. These results highlight the challenges and opportunities of meeting even basic human access needs to water and protecting aquatic ecosystems.

The global water cycle and, in particular, surface water and groundwater flows (blue water) have been greatly impacted during the Anthropocene[1]. Natural blue water flows, to which aquatic biota are evolutionarily adapted, underpin the health of freshwater ecosystems that, in turn, provide a range of ecosystem services to communities worldwide[2]. Freshwater wetlands provide a range of high-value services, including cleansing polluted water and recharging groundwater aquifers[3], and mangroves are vital to the livelihoods of many coastal communities in the tropics[4]. Inland fisheries, including aquaculture production, that depend on freshwater flows[5] contribute over 40% of the world's capture finfish fisheries[6], and over 70% of the world's coastal and estuarine fish catch comes from species that rely on freshwater flows to oceans[7].

Alteration of surface water flows through water withdrawals and consumptive uses, driven primarily by irrigation for agriculture and the widespread proliferation of dams[8], has had considerable impact on aquatic and terrestrial ecosystems worldwide, putting natural systems and their provision of ecosystem services at risk[9]. Substantial declines in groundwater, driven by climatic variation and overuse by agriculture and water supply[10], have led to widespread land subsidence, deterioration of groundwater-dependent ecosystems, reduced surface water flows and increasing costs of water extraction[11]. Saltwater intrusion into coastal aquifers and reductions in water quality from groundwater pollution also reduce water availability for domestic and agricultural use[12]. The broad range of biophysical impacts from alterations to blue water flows are often disproportionately felt by

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Table 1 | Population in each continent living in river basins where human needs at different access levels cannot be met with surface water alone, while remaining within the safe and just ESBs

Access levels (litres per person per day)	Global	Africa	Asia	Australia	Europe	North America	South America
Domestic, level 1 (50 l)	699 (0.09)	147 (0.11)	523 (0.11)	<1 (0.004)	4 (0.01)	21 (0.03)	4 (0.01)
Domestic, level 2 (100 l)	950 (0.12)	204 (0.15)	670 (0.14)	<1 (0.004)	20 (0.03)	25 (0.04)	31 (0.07)
All needs, level 1 (293 l)	2,329 (0.29)	355 (0.26)	1,639 (0.35)	3 (0.15)	161 (0.22)	110 (0.17)	61 (0.14)
All needs, level 2 (406 l)	2,619 (0.33)	409 (0.30)	1,723 (0.36)	9 (0.42)	241 (0.33)	167 (0.26)	69 (0.16)

Domestic access levels account for personal water use in the home, and 'All needs' levels account for household water use as well as blue water required for food and energy production and household infrastructure. Population numbers are in millions, and numbers in parentheses show the proportion of the total population globally and within each continent.

vulnerable communities owing to the loss of access to water and the ecosystem services it delivers[13].

An attempt to quantify the maximum allowed human alteration of the global hydrological cycle on land was carried out as part of the planetary boundary framework[14], defining the global freshwater boundary as the limit of human withdrawals for consumptive blue water use. This was a proxy for the alteration of both green (soil moisture generating evaporation and transpiration flows) and blue water partitioning (safeguarding a minimum level of environmental water flows)[15]. Recently, green water alterations were added to the planetary boundary assessment, and it was concluded that human shifts of soil moisture exceed the maximum range of variability over the recent Holocene, suggesting that green water alterations are today outside of the safe operating space[16]. These shifts in green water flow alter moisture recycling from land, affecting atmospheric rivers and downwind rainfall. As 50% of terrestrial rainfall on average originates from green water flows (the remaining from the ocean), these shifts impact future rainfall and blue water flows[17]. The urgency of recognizing that humanity is altering the source of all blue and green water—precipitation—through climate change and shifts in moisture recycling has been recently highlighted[18].

Building on the previous planetary boundaries for water, safe and just Earth system boundaries (ESBs) for surface water and groundwater have recently been proposed[19] to provide guidance on these critical issues, drawing on defined needs for minimum access to water[20] and the principles of Earth system justice[21]. Earth system justice is defined here as intragenerational (between today's countries, communities and individuals), intergenerational (between past, present and future generations) and interspecies (between people and nature) and includes both distributional and procedural justice[21]. In this context, the safe and just ESBs for blue water were defined to protect aquatic ecosystems and the services they provide[19].

Flow-ecology research has identified the importance of critical components of the natural flow regime, including the timing, quantity and quality of water flows[22]. The general findings from this research were used to define the safe and just ESBs for surface water at the river basin scale as ±20% alteration of monthly flows, leaving 80% of monthly flows unaltered for the environment[19,23]. The safe and just ESB for groundwater was defined as an average annual drawdown from both natural and anthropogenic causes no greater than average annual recharge, to ensure there was no decline in aquifer depth[19]. These sub-global ESBs were defined for individual river basins and aquifers. To meet them at the global scale requires 100% of all land surface areas to be within the sub-global ESBs.

The framework of ESBs can be used to operationalize and quantify intragenerational justice in terms of preventing exposure of people to significant harm[21]. Protecting surface water and groundwater systems while providing water for a broad set of human needs represents a considerable challenge for Earth system justice[19,21]. This concern is particularly acute in impoverished and water-scarce regions that already face challenges in meeting the basic needs of local populations owing to water shortages, poor water quality, highly inequitable access, water being diverted to other uses or a combination of these[24]. These

areas are often disproportionately affected by increasing climate variability[25]. In general, providing a minimum level of access to resources for all people can be achieved through reduction and reallocations of resource consumption, especially to the most vulnerable and those without access, as well as transformational changes in technology, governance and other key drivers[26].

Defining a minimum access level to water is an inherently fraught but important exercise given the importance of water to survival and well-being[27]. A study[20] estimated two minimum levels of blue water access needs for well-being, including daily domestic water use, energy production, infrastructure for housing and mobility, and the blue water footprints of key crops (293 l per person per day (level 1) and 406 l per person per day (level 2)). Although not fully addressing all dimensions of justice, defining access for the blue water share of human needs offers a benchmark for comparison in meeting the basic well-being of all humans while maintaining a safe Earth system. A water scarcity assessment that identifies where these needs can be met while respecting the safe and just ESBs, and where they cannot, is a critical step to keep all humans within a safe and just corridor[19].

Here we conduct a set of river-basin-scale analyses of the blue water ESBs defined in a previous study[19] using the estimated minimum access levels for blue water[20], under the modelling assumption that human needs are met only from local sources (that is, within the river basin). The results of these analyses extend the analyses of a previous study[20] to identify where minimum human needs for blue water could be met while respecting the safe and just ESBs, and where demand-side and/or supply-side transformations would be required to achieve this. We combine global modelled data on surface water and groundwater availability, between 2000 and 2020, with estimated basic human access needs for blue water, for domestic use and food and energy production. Because surface water tends to be the first (and cheapest) source of water appropriated for human needs, we identify where we can and cannot respect the safe and just ESBs on an annual basis if all people have equal access only to the minimum levels of water described above, from within their respective river basins. For river basins where local surface water alone is insufficient to meet minimum needs without transgressing the surface water ESB, we estimate the proportion of annual groundwater recharge that would be required to meet this access shortfall. We also show where the annual groundwater recharge rate is itself in decline, highlighting how climatic variability (shifting overall vapour flows and generating more extreme events) and land system change (affecting moisture recycling) are amplifying the challenges of staying within the ESBs. Finally, we examine the current status of surface water alteration and identify the different types of supply- and demand-side transformation, including redistribution, needed to return to or stay within the ESBs for surface water while meeting human needs (from local blue water resources only). Supply-side transformations to find external sources of blue water would be required in basins where human needs cannot be met by local sources. Demand-side transformations to reduce the volumes of blue water use would be required where there are sufficient blue water resources, but the river basin is currently outside the ESBs. These analyses are conducted at the river basin scale and summarized by continent and at the global scale.
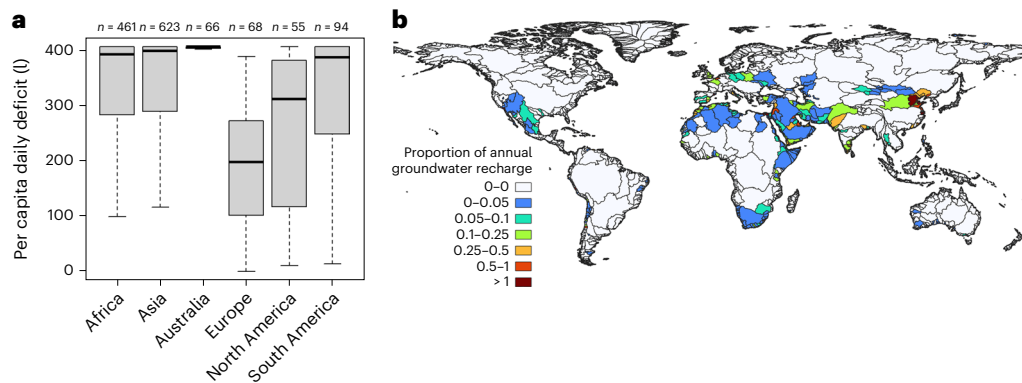
Fig. 1 | Surface water deficits and the groundwater required to meet them. a, The distribution of daily per capita deficits for all water needs (level 2) in each continent for river basins where these needs cannot be met by surface water flows alone. The top and bottom partitions of the grey boxes show the first and third quartiles, respectively, and the median is shown as a black line inside the box. The upper whiskers show the maximum values for each continent, and the lower whiskers are 1.5 times the interquartile range below the first quartile. The numbers of catchments in each continent are shown across the top of the graph. **b**, The proportion of groundwater recharge that would be required to meet the deficit in each river basin. River basins with no shading in **b** are those where there should be sufficient surface water to meet all needs at access level 2 (406 l per person per day).

Results

As expected, our results show that it would be challenging in many regions of the world to provide even basic access to water for all people from their local river basin while meeting the safe and just ESBs for surface water. We find that there is sufficient surface water availability, based on unmodified flows, to meet water access needs at domestic level 2 (100 l per person per day) for 88% of the world's population while remaining within the safe and just ESB for surface water (Table 1). However, 2.6 billion people live in river basins with insufficient annual surface water flows to provide level 2 access for all needs (406 l per person per day) and still remain inside the ESB (Table 1). This group represents one-third of the global population, with the majority living in Asia (1.7 billion). Despite the large number of people living under such circumstances, this represents only 5% of all river basins globally (Supplementary Table 2).

Meeting the safe and just ESB for surface water in regions that are relatively dry or have dense populations (for example, much of Africa, parts of Asia, and Australia) would create median daily per capita deficits close to 406 l based on level 2 access for all needs (Fig. 1a). In some parts of the world, these deficits could be met from a relatively low proportion of the average annual groundwater recharge, including river basins in southern Africa (for example, the Orange and Limpopo basins), where less than 5% of the average annual recharge would be needed (Fig. 1b). However, in many of the drier and more populous regions, for example, in eastern China, this would require 50% or more of the average annual groundwater recharge (Fig. 1b). The spatial patterns of current surface water flow alteration and groundwater decline are consistent with these findings (Supplementary Table 1 and Supplementary Fig. 1).

The average annual groundwater recharge (2003–2016) tends to be highest in equatorial regions (Fig. 2a). Nonetheless, there are regions in higher latitudes with high annual recharge volumes, such as parts of Scandinavia and northern Russia. Adding to the challenges facing drier and populous regions, the regions that also have relatively low volumes of groundwater recharge tend to be those where a higher proportion of the recharge would be required to meet the access levels of water, while remaining within the safe and just ESB for surface water (Figs. 1b and 2a). For example, in central and eastern China, up to 100% of the annual groundwater recharge would be required, and parts of the Middle East where recharge volumes are currently much lower would require 50%.

Compounding these challenges has been a trend of declining groundwater recharge in some regions, leading to a reduction in the local-scale safe and just ESBs for groundwater (red colours in Fig. 2b).

Some of these declines in groundwater recharge are associated with declining trends in annual rainfall volumes (grey hatching in Fig. 2b and Supplementary Fig. 2). For example, from 2003 to 2016, declines in annual groundwater recharge across the Indian subcontinent of up to 6 million m^3 yr^{-1} have occurred in conjunction with declines in rainfall of up to 10 mm yr^{-1} (indicated by the grey hatching over the red pixels showing the groundwater trend in Fig. 2b). Similarly, large regions of the South American continent have shown declining groundwater recharge associated with declining annual rainfall during this period. This is contrasted with regions where groundwater recharge has been declining without an associated decline in rainfall, such as parts of eastern Europe and central Africa (indicated by red pixels without any grey hatching in Fig. 2b).

We combined the capacity to meet access needs from unaltered surface flows (Fig. 1), the trend in groundwater recharge (Fig. 2b) and the current level of surface flow alteration (Supplementary Fig. 1a) to classify river basins into eight groups where transformations would be needed to transition back into the safe and just ESB (Figs. 3 and 4). These categories identify the number of people across the globe and in each continent where various transformations would be necessary to meet all level 2 access needs (406 l per person per day), using blue water resources from their local river basins only, while meeting the safe and just ESBs for surface water and groundwater. While some regions could rely on supply-side transformations by substituting a portion of surface water use with groundwater use to meet both access needs and safe and just ESBs, others would require substantial demand-side transformations.

There are almost 2.4 billion people living in river basins where only relatively modest transformations to water sources would be required (groups 1 and 3; Fig. 4). These locations have sufficient surface water flows to meet access needs, and flow alteration is not currently exceeding the safe and just ESB. They tend to be those with relatively high levels of flow, low levels of income and/or low population densities, such as the Amazon, Congo and Irrawaddy River basins (Fig. 3). The 2.6 billion people in groups 2 and 5 live in river basins where shifting from surface water to groundwater use (supply-side transformation) would provide the means to stay within the surface water ESB (group 2) or to meet access needs without exceeding the surface water ESB (group 5; Fig. 4). These include large river basins such as the Paraná, Zambezi and Yangtze, in group 2 (Fig. 3), as well as smaller rivers in drier parts of the world where the proportion of groundwater required to meet minimum access needs is relatively low, such as the Tana River in Kenya and the Orange River in South Africa (Figs. 1b and 3). However, using
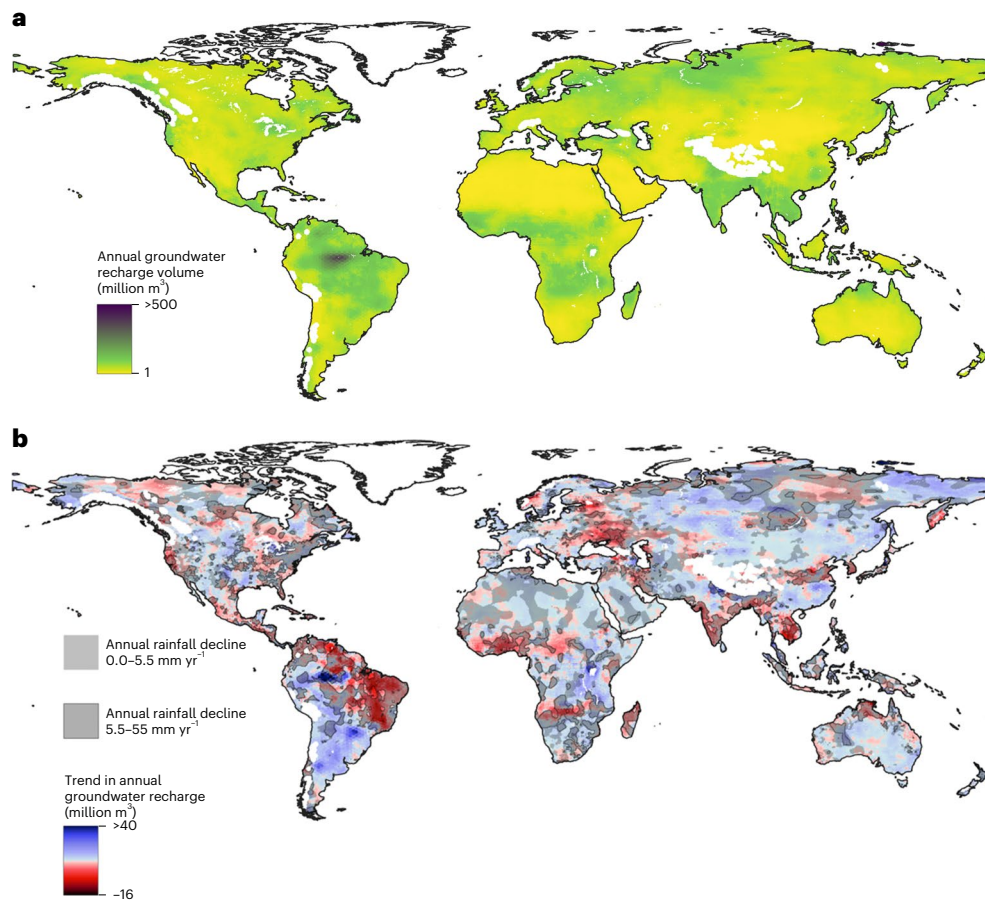
Fig. 2 | Groundwater recharge volumes and trends. a, Average annual groundwater recharge volume derived from GRACE[59], representing the safe and just volume of groundwater that can be drawn down annually (including natural groundwater discharge and anthropogenic extraction). **b**, The trend in annual recharge volume between 2003 and 2016, showing where annual recharge is declining (red areas) or increasing (blue areas). Grey hatching in **b** shows where there has been an associated decline in annual rainfall. Light grey hatching shows regions where declines have been below the 10th percentile (<5.5 mm yr⁻¹) while darker grey hatching shows where declines in rainfall have been above this threshold.

supply-side transformations would be more difficult in group 5 rivers where the proportion of groundwater that would be required to meet the access needs of dense populations and agriculture is relatively high, such as the Yellow and Indus Rivers (Fig. 1b).

There are 1.4 billion people living in river basins where demand-side transformations would be needed to meet the safe and just ESB for surface water (groups 4 and 7; Fig. 4). These include the Mekong and Niger River basins (Fig. 3) that are currently outside the safe and just ESB for surface water, despite having sufficient surface water flows to meet access needs, while groundwater recharge has been declining (group 4). Group 7 river basins are currently within the surface water ESB but do not have sufficient surface water flows to meet access needs, and groundwater recharge has been declining. The remaining 1.5 billion people live in river basins where a mix of transformations would be required as there is insufficient surface water to meet access needs and the level of flow alteration is already beyond the ESB for surface water (groups 6 and 8). Those living in group 6 river basins, which include the Yellow and Indus Rivers (Fig. 3), could potentially increase groundwater use as annual recharge has not been declining in recent years. However, groundwater recharge has been declining in group 8 river basins, which include the Chao Phraya River (Fig. 3), probably necessitating more substantive transformations in water use.

Discussion

We have conducted an analysis of the safe and just ESBs for blue water in the context of minimum access needs of populations. In doing so, we identified the river basins where basic water needs for all people could be met with surface water from within the river basin while staying within the safe and just ESB, supporting about two-thirds of the world's population. In the river basins where this would not be possible, we showed what proportion of groundwater recharge would be required to meet basic water needs and stay within the surface water ESB. We also showed that many parts of the world currently face declining groundwater recharge, illustrating the challenge of meeting the basic water needs of humans in a changing climate. In synthesizing this information with the current level of surface flow alteration (Supplementary Information), we identified where additional demand- and/or supply-side transformations could be mobilized to meet equal levels of minimum access needs for all humans and stay within the safe and just ESBs.

Our findings build on previous research on water scarcity by integrating the blue water required to provide minimum access to basic human needs while staying within the safe and just ESBs for blue water, based on environmental flow requirements. The outcome will differ from those of previous water scarcity assessments that have used lower environmental flow requirements or derived human needs using other methods. It has been argued that the approach used here for the surface water ESB is too stringent for water scarcity assessments[28]; however, there is growing evidence that surface flow alterations beyond this level substantially impact aquatic ecosystems and the services they provide[19]. Many previous water scarcity studies used indices such as population and existing cropland distribution to define the blue water requirements for people[28]. Others used the food production required
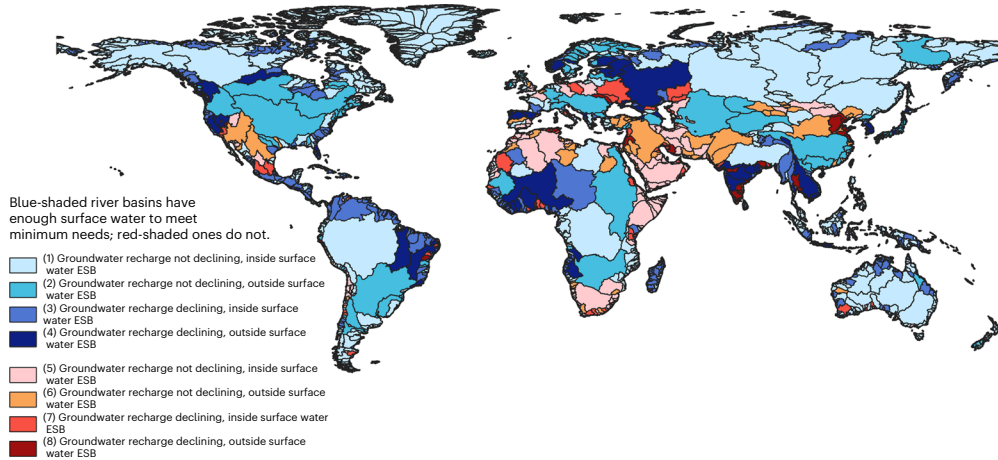
Fig. 3 | Classification of river basins in the context of the ESBs. The eight groups of river basins as defined by the status of their surface water and groundwater with respect to the safe and just ESBs (Fig. 4).
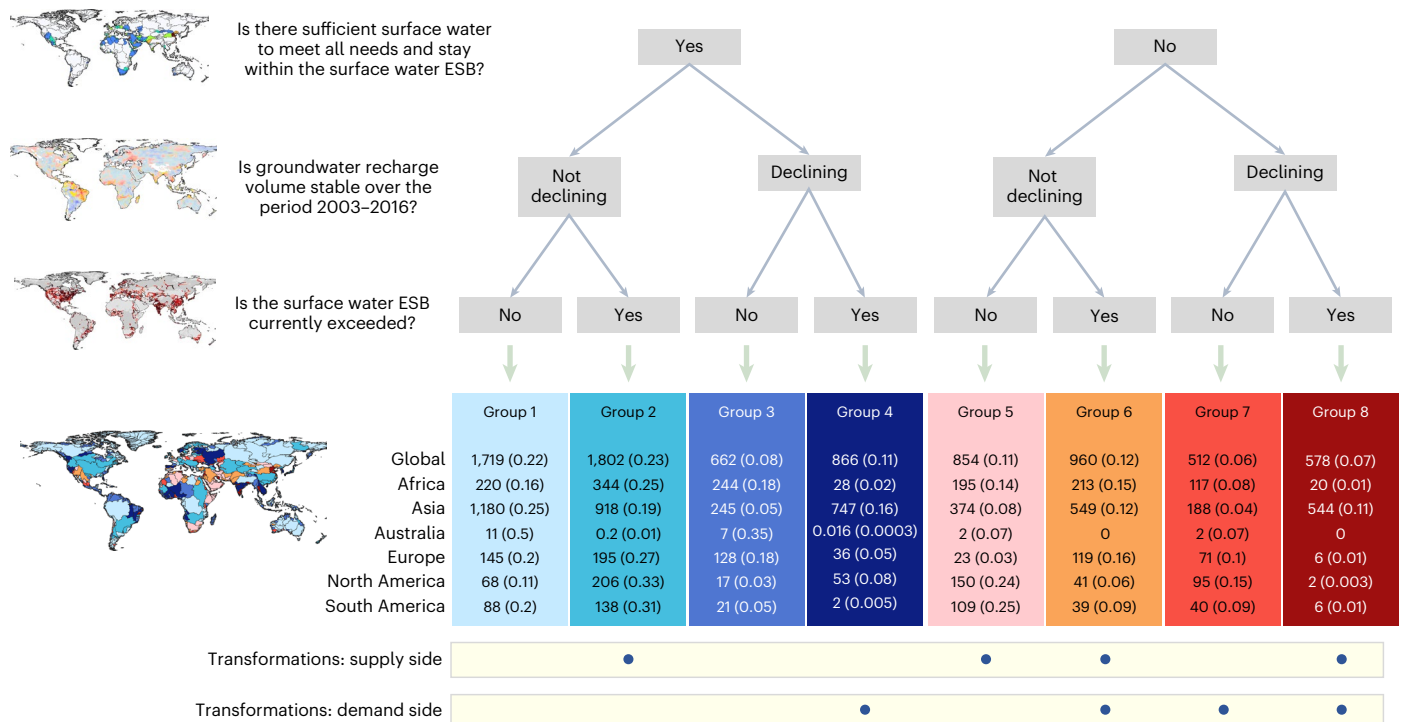

Fig. 4 | Populations in each group of river basins. Populations living in different river basins, classified according to (1) whether there should be sufficient (unaltered) surface water flows to meet all needs at access level 2, (2) whether groundwater recharge is stable or has been declining over the period of record and (3) whether we are inside or outside the surface water ESB on an annual basis based on current surface water flows (Supplementary Fig. 1a). Populations are estimated globally and by continent. Population numbers are in millions, and numbers in parentheses show the proportion of the total population, globally and within each continent, in each group. Blue dots indicate the type of transformations that are probably required to meet minimum access needs while meeting the safe and just ESBs. See Figs. 1–3 and Supplementary Fig. 1a for the full-size versions of the maps on the left.

for a healthy diet for all people to determine blue and green water requirements[29,30], and including both water sources is increasingly recognized as an integral component of water scarcity assessments[31]. While our study focused on blue water only, we included additional demands on blue water to meet basic human needs for food, infrastructure and energy. The inclusion of such a broad range of blue water demands in concert with ecologically defined ESBs points to the potential demand- and supply-side transformations that may help river basins move inside the ESB.

Demand-side transformations could include a transition to less water-intensive foods and other products that are produced in the local river basin for domestic consumption and export[32]. They could also include improvements in the efficiency of water use within the river basins including reducing leakage in urban water distribution systems, and particularly in agricultural production, which accounts for approximately 70% of flow alterations globally[33]. There is substantial uncertainty in global estimates of irrigation efficiency[34], and observed improvements have not always been accompanied by reductions in water use, indicating that transformative policies, such as progressive pricing on water use, need to be accompanied by suitable regulatory frameworks and improved water accounting[35]. Nonetheless, there are still many opportunities for further improvements in irrigation

efficiency around the world but particularly in river basins in south Asia and sub-Saharan Africa[36] that are currently exceeding the surface water ESB. Demand-side improvements such as these can also reduce some of the supply-side challenges.

Supply-side transformations for domestic water supply could include a transition to different sources of water, such as local groundwater, safely treated recycled water or inter-basin transfers from more water-abundant river basins (providing that the source basin would remain within the ESBs and the risks to biodiversity from accidental translocation of invasive species are managed effectively). Supply-side transformations to meet basic food needs with reduced surface water and groundwater demand could include greater reliance on the agricultural use of green water, which is the water that is naturally available in the root zone (noting that the planetary boundary for green water may have already been transgressed[16]), and other sources such as recycled water to reduce alteration of local blue water flows. Inevitably, these transformations come with economic, environmental and social costs and risks, such as the increased costs of groundwater pumping and the subsequent risk of overuse of subsurface waters[37]. Moreover, such changes will have to grapple with existing property rights regimes to water in many parts of the world[38] that allocate water resources to landowners, permit holders and contractual parties but may stand in the way of redistributing water from one use to another, to those without access and from one user to another. Guaranteeing procedural justice, which highlights the inclusion of all stakeholders, including Indigenous peoples, and consideration of ecosystem needs for interspecies justice[21] in such transformations will be key.

Transforming blue water use among different supplies and needs in river basins that are already outside the ESBs will most probably require a mix of supply- and demand-side transformations. In many basins, supply-side transformations to use more groundwater may help meet the surface water ESB; however, in doing this, they may risk transgressing the groundwater ESB. The ESB for groundwater does not prescribe a volume of extraction that can occur, only that total annual drawdown should not exceed long-term average annual recharge. This necessitates local-scale monitoring, missing in many regions, to determine levels of extraction, given the groundwater recharge from the previous year. Meeting this boundary should ensure that extraction of groundwater does not further alter surface water flows, a risk in regions where return flows from extraction are low[39], and complements a previously defined presumptive standard for groundwater extraction[40].

The analyses in this study focus on demand for blue water that arises from within local catchments, which is water for domestic use and as an input in the production of goods that takes place in the same catchment. We did not integrate virtual (also termed embodied) blue water flows, which are movements between locations through the export and import of products derived from and containing blue water[41]. Many water-scarce regions import food produced in water-abundant regions to supplement local production[42]. Analyses of blue water flows show that around 15–30% of water used in agricultural production is exported to other river basins and countries[43]. This is very unevenly distributed, with a relatively small number of countries and agricultural products accounting for a large proportion of international virtual water trade[44]. Although virtual water movement may result in blue and green water savings at the global scale[45], it can contribute substantially to the alteration of flows in some parts of the world[44]. As such, transformations based on virtual water trade to bring a river basin inside the ESBs, such as a transition away from water-intensive exports, may not necessarily solve problems of water scarcity elsewhere.

Transformations via virtual water trade will be critically important in large cities, where safe and just allocations of blue water are unlikely to be sufficient to meet minimum access needs[46] and local agricultural production is very limited. Such transformations inevitably come with inherent costs, which are likely to be incremental and require strategic development in the local context[47]. Local-scale assessments can help identify suitable potential transformations that can accommodate the costs of water supply based on water availability and infrastructure costs. For example, our analysis shows that Beijing is in a river basin in the highly populous region of the North China Plain where there is insufficient surface water to meet minimum access needs from the local river basin while remaining within the ESB. The basin is already outside the surface water ESB and groundwater recharge has been declining. This suggests that the integration of supply-side and demand-side transformations would be required to live within the safe and just ESBs while meeting the needs of the population. A recent optimization showed how a different allocation among various water sources, including local surface water and groundwater, inter-basin transfers and virtual water, could be used to meet the demand of the different sectors in the city while minimizing costs of water supply[48]. Approaches such as these can be applied with the additional constraints of the safe and just ESBs for blue water to identify avenues to meet access needs without transgressing the ESBs; however, to ensure just as well as safe outcomes, they must be grounded in principles of Earth system justice[21].

The basis of the total blue water requirement for access levels 1 and 2 is household water consumption, irrigation required for agriculture, water required for household energy production and water embodied in household infrastructure (Table 2)[20]. Absent from these calculations are other important water demands that are necessary to improve incomes and livelihoods, such as water use for agricultural exports, manufacturing and industry, education and hospitals. As such, we have under-estimated the number of river basins that do not have sufficient water available to meet minimum access needs and remain within the ESBs. River-basin-scale decision-making on water use and supply must accommodate a wider array of needs such as energy production, which can involve substantial flow alteration under hydroelectric schemes[49], as well as treatment of poor water quality that effectively reduces water availability and impacts aquatic ecosystems. These additional human needs, along with the extent to which current flow alterations have already led to a global water crisis[50], emphasize the importance of transformations to water supply and demand. Achieving the practical, basin-scale transformations discussed here will require a dramatic shift in the way water is valued, with transformations to the policy and regulatory frameworks that govern water[50].

Meeting the safe and just ESBs for all domains of the Earth system is going to be challenging, and blue water offers a unique challenge given that it is essential to human survival and the current inequalities in access to water. The ESBs for blue water were developed to protect the Earth system and the ecosystem services that aquatic ecosystems provide to humans. Meeting them will require radical and systemic transformations of human systems, including renegotiation of international water-sharing agreements as well as education of the public and policymakers, to ensure that the basic needs of all people can be met and that there is water available for sustainable development. This is increasingly pressing given the ongoing challenges to Earth system stability including projected population growth and increasing urbanization and the hydrological impact of climate change and subsequent impact on aquatic ecosystems. Nonetheless, it is essential to ensuring a safe and just future for all people and the planet's blue water systems.

Methods

We have used a series of analyses to operationalize the safe and just ESBs for blue water. The first was to quantify, based on the estimates of minimum access needs from a previous study[20], whether we have sufficient surface water flows to meet the minimum water needs of all people relying on local surface water alone and help them escape poverty. The second was to quantify what proportion of groundwater recharge we would need to draw on to meet human needs while respecting the surface water ESB. The third was to quantify the trend in annual groundwater recharge and annual rainfall volumes to identify regions where the trend of annual groundwater recharge is in decline.

Table 2 | Minimum water needs defined by a previous study[20] to maintain a dignified life and to escape from poverty

Water demand metric	Litres per capita per day	Litres per capita per year
Domestic, access level 1 (dignity)	50	18,250
Domestic, access level 2 (escape from poverty)	100	36,500
All needs, access level 1 (dignity)	292.85	106,890
All needs, access level 2 (escape from poverty)	405.67	148,069

Finally, we combined the first and third of these analyses with a global-scale quantification of where we are already outside the ESBs for surface water to derive the classifications of each river basin according to the different types of supply- and demand-side transformation that may be necessary.

We used the two levels of access to blue water[20] required for basic human needs. These estimates were based on daily domestic water use and water required for energy, infrastructure for housing and mobility, and the blue water footprints of key crops to meet basic needs for food. The two levels of daily domestic water use considered here are a minimum (50 l per person per day) required to maintain basic dignity (not just survival) and a slightly higher level (100 l per person per day) required to escape from poverty. These were derived from the intermediate and optimal level of access for daily domestic needs, including sanitation, defined by the World Health Organization[20,51]. Including the blue water requirements to meet access needs for food, energy and infrastructure[20] increases this to 293 l per person per day (level 1) and 406 l per person per day (level 2). Billions of people do not have access to this basic level of water, but many others use much more, with the global average water use around 1,500 l per person per day[20]. Meeting all water requirements for domestic, industry, food (adequate diet of 2,500 kcal per person per day) and energy equally for all would require more than twice this volume, but note that this would be derived from a combination of blue and green sources[18]. Here we analyse the blue water component only.

We converted the two levels of daily water needs[20] to total annual per capita volumes of water required for basic human needs (Table 2, adapted from a previous study[20]). The two access levels of 'all needs' represent the demand on the hydrological cycle and include the same domestic needs and the volume of water required to produce food, energy and infrastructure at the two access levels. See ref. 20 for the full methodology used to derive these numbers.

1. Surface water flows to meet minimum human needs

We compared the volume of water that was available under the safe and just ESB at the river basin scale with the different volumes of water to meet human needs.

The daily per capita water needs were converted to spatially distributed gridded annual volumes by multiplying the demand metrics by a distributed population dataset for 2020[52] and then summed over river basins. Long-term mean annual discharge and available surface water discharge at the basin mouth are used to define integrated water flows for the river basins. Where the annual alteration budget under the ESB for surface water was greater than the per capita water needs for the resident population, we determined that it is possible to meet human needs from water within that river basin while meeting the ESB. Where the annual alteration allowed under the ESB was less than the per capita water needs for the resident population, we determined that it is not possible to meet human needs from water within that river basin while meeting the ESB, creating a 'safe water deficit'. For the purposes of this analysis, we made no assumptions around water storage capacity or monthly alteration levels that would be required to meet these human needs.

2. Groundwater for meeting human needs

In river basins where we cannot meet safe water needs with surface water from within the basin, we may be able to rely on groundwater recharge to meet these needs. To quantify the extent to which groundwater recharge would be required, we converted safe water deficits for 'All needs' at access level 2 to a proportion of the total annual groundwater recharge. We summed groundwater recharge volumes over river basins for these basin-level calculations. We calculated the proportion of groundwater needed to meet the safe water deficits as the ratio of the 'safe water deficit' and the 'average annual recharge volume'.

3. Estimating groundwater recharge volumes in decline

We identified pixels, and then river basins, where groundwater recharge volume was in decline by quantifying the annual recharge in a given pixel and then quantifying the trend in the annual recharge. At the river basin scale, we calculated the average trend of all pixels in each river basin to define the status of whether recharge has been in decline in that basin or not. We accompanied this with similar analyses of annual rainfall volumes to identify where declining groundwater recharge volumes are associated with declining annual rainfall.

4. River basins outside the surface water ESB

We identified river basins that are already outside the safe and just ESB for surface water by comparing modelled observed (altered) monthly flows with modelled pristine (unaltered) monthly flows. We calculated 20% of the long-term mean annual pristine flows at grid cells throughout global river networks as a spatially distributed volume of annual alteration that is within the safe and just ESB, leaving 80% of annual flows unaltered to protect aquatic ecosystems and the ecosystem services they provide. To quantify the extent to which river flows are outside the safe and just ESB in a given river basin, we first calculate the number of months in a year when the contemporary altered flows are more than 20% different from pristine flows using the long-term mean gridded discharge data. We then represent these data as the proportion of months in a year with more than 20% difference for each grid cell in the global river networks. For the purposes of the spatial analyses, we defined a river basin as being outside the safe and just ESB when the long-term mean observed total annual discharge at the river mouth was more than 20% different from the long-term mean pristine total annual discharge[19]. We used total annual discharge for this analysis for comparison with the groundwater ESB, which is on an annual time step.

We identified regions that were outside the safe and just ESB for groundwater by comparing the long-term trend in groundwater storage volumes. Regions where the average annual drawdown exceeded the average annual recharge showed an ongoing decline in groundwater storage and were defined as being outside the safe and just ESB for groundwater.

Global surface water hydrology

We derived the pristine and altered monthly river flow datasets from the water balance model (WBM) river discharge outputs[53] at a 6 min grid-cell resolution using the TerraClimate high-resolution dataset of monthly climate forcings[54] for the period 2000–2020 using Python version 3.9.7. River basin delineation and flow routing configurations are defined by the WBM 6 min topological river network used to establish local discharge and river flow[53]. The pristine and altered WBM runs use the same climate forcings for the 2000–2020 time period, but the altered runs use human alterations to the water cycle, including water extraction for irrigation and large reservoirs as an indicator of flow alteration. As the WBM disturbed model runs do not include smaller alterations not associated with dam operations, such as direct extraction for stock and domestic water, we may under-estimate the extent to which a given basin is outside the surface water ESB. Nonetheless, the modelled long-term mean contemporary global annual discharge of 38,000 km³ under this scenario is consistent with other results from the literature[55,56].

Long-term mean monthly discharge is calculated for the modelled pristine (non-human impacted) and altered (human impacted) discharge from the WBM over the 2000–2020 time domain to determine the extent of altered flow. The analysis is limited to only the perennial or actively flowing river extents by applying a 3 mm yr^{-1} upstream monthly average runoff exceedance threshold[57] occurring for at least 10 years out of the 2000–2020 time domain. We also mask out upstream headwater areas (smaller than 250 km^2) that have modelled irrigation depths below the median irrigation depth for small headwater cells (3.6 mm yr^{-1}). This mask is applied to eliminate noise in the modelled data associated with very low irrigation and discharge values in headwater grid cells. The river network and river basin extents, including the continent definitions, are given by the WBM[53,57], with the naming convention taken from the Global Runoff Data Centre Major River Basins of the World[58]. We used QGIS version 3.38.8 for mapping and R version 4.2.1 and Excel 365 to summarize the data tables.

Global groundwater dynamics

Hydrological measurements of volumetric changes in aquifer storage are critical in assessing groundwater status, but these measurements are considerably limited in several regions of the world[10]. Given that the aquifers in some regions are typically not monitored, global-scale assessments of baseline aquifer volumes are difficult. To circumvent this, the Gravity Recovery and Climate Experiment (GRACE[59]) mission has been used to track changes in several large aquifer systems around the world[60]. In this study, changes in groundwater were quantified using the GRACE data covering the period 2003–2016 (data files are accessed at http://www2.csr.utexas.edu/grace/RL06_mascons.html). GRACE measures monthly changes in terrestrial water storage (TWS), which is the sum of soil moisture, groundwater, surface water, snow water and canopy storage and is expressed as:

$$TWS = SMS + GWS + SWE + SWS + CS \qquad (1)$$

where SMS is the soil moisture storage change, GWS is the change in groundwater storage, SWE is the change in snow water equivalent, SWS is the change in surface water storage (that is, inland surface and reservoir storage) and CS is the water storage change in canopy. To quantify GWS, equation (1) was rearranged such that SMS, SWE and CS, which are model-derived outputs from the Global Land Data Assimilation System (GLDAS) Noah Land Surface Model L4 v2.1 (ref. 61), were subtracted from TWS. Hydrological outputs (for example, SMS, SWE and CS) obtained from model simulations may be characterized by large uncertainties owing to inadequate in situ data for calibration and parameterization, as well as the presence of strong interannual and seasonal variability in surface reservoirs and snow- and ice-cap storage in some regions. In some regional groundwater studies, the effects of interannual changes in surface water component, such as those from major lakes and reservoirs, are significantly strong and have been reasonably managed and removed from the GRACE-observed TWS using data reconstruction and synthesized kernel functions[62,63]. However, a global-scale groundwater processing protocol or the isolation of surface water footprint from the GRACE hydrological water column using model simulation is rather impracticable and not feasible. Alternatively, the water storage components (SMS, SWE, SWS) in equation (1) have been captured in the WaterGAP Global Hydrology Model (WGHM)[64], and directly subtracting these WGHM outputs from TWS will result in groundwater changes. The uncertainties in these WGHM water storage components are unknown and arguably could amplify the estimated groundwater changes from TWS, especially in regions where WGHM outputs performed poorly (for example, refs. 60,63).

To cushion the effect of such errors and uncertainties that may be propagated from this approach, much of the regions with substantial inland surface water storage changes (for example, Caspian Sea, Black Sea, Lake Victoria and other significant water bodies) were masked out

(regions with no groundwater signal). In addition, uncertainties caused by residual ice and snow cover from areas (for example, Patagonia, Alaska, the Himalayas, the Swiss Alps) with large variations were minimized by masking such regions using the world distribution of glaciers and ice-cap extents (geospatial data layer showing boundaries of such glaciers). This decision acknowledges the higher uncertainties in the simulations of these quantities by the GLDAS model. Furthermore, some glaciers are small and may be obscured, but a buffer zone of 1° was created to help flag and remove such glaciers. Overall, the groundwater estimation process here is based on the water budget approach, which has been widely used in GRACE-derived groundwater storage studies (for example, refs. 65,66). There are several GRACE-TWS products available from different providers, but the TWS data used in our study are a mass concentration (mascon) product (GRACE RL 06 version 02) obtained from the Center for Space Research. These mascon products are preferred to other GRACE solutions (for example, those based on spherical harmonics) as they exhibit less signal leakage and a posteriori filtering is unnecessary as the mascon product relies on geophysical constraints to suppress noise in the data (for example, ref. 67).

The estimated annual recharge volume used in this study was based on the time series of groundwater anomalies. For each groundwater pixel, annual recharge was calculated by quantifying the difference between the maximum groundwater depth in a given year and the shallowest observation of the preceding year (Supplementary Fig. 3). The annual recharge depth at each GRACE pixel was converted to a volume by multiplying the area of the pixel. As such, our estimate of annual recharge volume is the net of aquifer discharge, recharge and any groundwater abstraction that may have occurred at a given location. Accurate assessment of recharge using modelling techniques and chloride mass balance could be challenging because groundwater recharge is governed by complex interactions, including the relationship of climate change (for example, prolonged drought) and human water abstraction with land surface conditions (for example, increased evapotranspiration), geology and differences in water yield, among other factors. However, we found that our recharge estimates broadly aligned with some proposed estimates in the literature and other reports[68].

Areas categorized as under risk of groundwater stress (that is, groundwater storage being in decline) were identified by computing the difference between the estimated annual recharge and drawdown (Supplementary Fig. 1b). Using the aggregated monthly groundwater data, drawdown was quantified as the maximum groundwater values of a specific year less the observed minimum values of the following year. Notably, this drawdown varies in time and space and could be human or climate driven. The spatial distribution of trends in the time series of global annual recharge and groundwater storage (Supplementary Fig. 1b) was estimated using the least squares approach.

Trends in annual rainfall volume

The trends (mm yr^{-1}) in annual rainfall were based on monthly Global Precipitation Climatology Centre (GPCC) precipitation data (mm). The GPCC-based precipitation is one of the widely used gridded rainfall products because it consists of quality-controlled observational data from 67,200 gauged stations worldwide[69]. The GPCC data are available on a 0.25° spatial resolution and were accessed from the NOAA repository (https://psl.noaa.gov/data/gridded/data.gpcc.html). The monthly grids (spatial and temporal dimensions) of GPCC rainfall were generated from the scientific file format (popularly called Network Common Data Form) and accumulated to annual values using scripts written in Matlab R2018A version, underpinned by the Mapping and Aerospace Toolboxes. The least squares approach was then used to estimate the trends in the time series of the annual rainfall data for the period between 2002 and 2016, consistent with other data used in this study.

Methodological limitations

The volumes of water required to meet daily needs include a mix of consumptive and non-consumptive uses. The blue water footprints

used to calculate water needs for food production are consumptive footprints based on net extraction, deducting return flows from withdrawals, but water access for daily domestic use is based on withdrawals and does not account for return flows. While this means that some of this water may be returned to the river and may result in an inconsistent estimate of the volumes of water extracted from surface water flows over time, it will result only in an under-estimate of the impact of the initial alterations against the surface water ESB. This is because the surface water ESB is about the extent of flow alteration, not consumptive use. Alterations of flow are known to have significant ecological impacts regardless of whether flows return to the river downstream or at a later time. For instance, the timing and duration of return flows reaching the channel vary and do not necessarily prevent a change to the timing of peak flows and the duration of low flows due to the initial flow withdrawal (for example, at the river basin scale[70] and at the global scale[71]). These peak-flow and low-flow events are often critical flow events upon which aquatic ecosystems rely[72,73]. In addition, we do not include water quality in the surface water ESB, and it is common for return flows to have lower water quality without local remediation (for example, ref. [74]), which will also impact aquatic ecosystems. As such, the return flows themselves are not necessarily a substitute for naturally flowing river flow that delivers aquatic ecosystem services and we probably under-estimate the impact of the consumptive water footprints for food production because they will come from a higher level of flow alteration than the consumptive use alone would indicate.

We have conducted this study on an annual basis to align the temporal resolution of the two blue water ESBs. The ESB for groundwater is defined on an annual basis, that average annual drawdown due to both natural seasonal declines and anthropogenic extraction should not exceed average annual recharge. However, the ESB for surface water is that flow alterations due to anthropogenic causes in a given basin should not exceed 20% of natural flows each month. Aggregating flow alterations to an annual time step allowed us to make direct comparisons with the groundwater ESB; however, the temporal nature of violations of the surface water ESB (Supplementary Fig. 1a) is not apparent.

Reporting summary

Data availability

The groundwater data were derived from GRACE (http://www2.csr.utexas.edu/grace/RL06_mascons.html) and the GLDAS (https://disc.gsfc.nasa.gov/datacollection/GLDAS_NOAH025_3H_2.1.html). Annual rainfall data came from the GPCC precipitation data (mm) available at https://psl.noaa.gov/data/gridded/data.gpcc.html. The data for the surface water hydrology were derived from existing published datasets[53,57].

Code availability

The code for the groundwater recharge, rainfall and groundwater data processing in this paper is available at https://doi.org/10.5281/zenodo.8361529. The code for surface water hydrology data processing in this paper is available at https://doi.org/10.5281/zenodo.8343035.

References

1. Falkenmark, M., Wang-Erlandsson, L. & Rockström, J. Understanding of water resilience in the Anthropocene. *J. Hydrol. X* **2**, 100009 (2019).
2. Rinke, K., Keller, P. S., Kong, X., Borchardt, D. & Weitere, M. in *Atlas of Ecosystem Services: Drivers, Risks, and Societal Responses* (eds Schröter, M. et al.) 191–195 (Springer International Publishing, 2019); https://doi.org/10.1007/978-3-319-96229-0_30
3. Mitsch, W. J. & Gosselink, J. G. *Wetlands* (John Wiley & Sons, 2015).
4. Bimrah, K., Dasgupta, R. & Saizen, I. in *Assessing, Mapping and Modelling of Mangrove Ecosystem Services in the Asia-Pacific Region* (eds Dasgupta, R. et al.) 239–250 (Springer Nature, 2022); https://doi.org/10.1007/978-981-19-2738-6_13
5. McIntyre, P. B., Reidy Liermann, C. A. & Revenga, C. Linking freshwater fishery management to global food security and biodiversity conservation. *Proc. Natl Acad. Sci. USA* **113**, 12880–12885 (2016).
6. Lynch, A. J. et al. The social, economic, and environmental importance of inland fish and fisheries. *Environ. Rev.* **24**, 115–121 (2016).
7. Broadley, A., Stewart-Koster, B., Burford, M. A. & Brown, C. J. A global review of the critical link between river flows and productivity in marine fisheries. *Rev. Fish Biol. Fish.* **32**, 805–825 (2022).
8. Döll, P. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environ. Res. Lett.* **4**, 035006 (2009).
9. Borgwardt, F. et al. Exploring variability in environmental impact risk from human activities across aquatic ecosystems. *Sci. Total Environ.* **652**, 1396–1408 (2019).
10. Rodell, M. et al. Emerging trends in global freshwater availability. *Nature* **557**, 651–659 (2018).
11. Famiglietti, J. S. The global groundwater crisis. *Nat. Clim. Change* **4**, 945–948 (2014).
12. Basack, S., Loganathan, M. K., Goswami, G. & Khabbaz, H. Saltwater intrusion into coastal aquifers and associated risk management: critical review and research directives. *J. Coast. Res.* **38**, 654–672 (2022).
13. Pradhan, A. & Srinivasan, V. Do dams improve water security in India? A review of post facto assessments. *Water Secur.* **15**, 100112 (2022).
14. Rockström, J. et al. A safe operating space for humanity. *Nature* **461**, 472–475 (2009).
15. Gerten, D. et al. Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. *Curr. Opin. Environ. Sustain.* **5**, 551–558 (2013).
16. Wang-Erlandsson, L. et al. A planetary boundary for green water. *Nat. Rev. Earth Environ.* **3**, 380–392 (2022).
17. Tuinenburg, O. A., Theeuwen, J. J. E. & Staal, A. High-resolution global atmospheric moisture connections from evaporation to precipitation. *Earth Syst. Sci. Data* **12**, 3177–3188 (2020).
18. Rockström, J., Mazzucato, M., Andersen, L. S., Fahrländer, S. F. & Gerten, D. Why we need a new economics of water as a common good. *Nature* **615**, 794–797 (2023).
19. Rockström, J. et al. Safe and just Earth system boundaries. *Nature* **619**, 102–111 (2023).
20. Rammelt, C. F. et al. Impacts of meeting minimum access on critical earth systems amidst the Great Inequality. *Nat. Sustain.* **6**, 212–221 (2023).
21. Gupta, J. et al. Earth system justice needed to identify and live within Earth system boundaries. *Nat. Sustain.* https://doi.org/10.1038/s41893-023-01064-1 (2023).
22. Arthington, A. H. et al. The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018). *Front. Environ. Sci.* **6**, 45 (2018).
23. Richter, B. D., Davis, M. M., Apse, C. & Konrad, C. A presumptive standard for environmental flow protection. *River Res. Appl.* **28**, 1312–1321 (2012).
24. van Vliet, M. T. H. et al. Global water scarcity including surface water quality and expansions of clean water technologies. *Environ. Res. Lett.* **16**, 24020 (2021).
25. Misra, A. K. Climate change and challenges of water and food security. *Int. J. Sustain. Built Environ.* **3**, 153–165 (2014).

26. O'Brien, K. Is the 1.5 °C target possible? Exploring the three spheres of transformation. *Curr. Opin. Environ. Sustain* **31**, 153–160 (2018).

27. Gupta, J. & Lebel, L. Access and allocation in earth system governance: lessons learnt in the context of the sustainable development goals. *Int. Environ. Agreem.* **20**, 393–410 (2020).

28. Liu, J. et al. Water scarcity assessments in the past, present, and future. *Earths Future* **5**, 545–559 (2017).

29. Rockström, J. et al. Future water availability for global food production: the potential of green water for increasing resilience to global change. *Water Resour. Res.* **45**, W00A12 (2009).

30. Gerten, D. et al. Global water availability and requirements for future food production. *J. Hydrometeorol.* **12**, 885–899 (2011).

31. Liu, W., Liu, X., Yang, H., Ciais, P. & Wada, Y. Global water scarcity assessment incorporating green water in crop production. *Water Resour. Res.* **58**, e2020WR028570 (2022).

32. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018).

33. Molden, D. (ed.) *Water for Food Water for Life: A Comprehensive Assessment of Water Management in Agriculture* 1st edn. (Routledge, 2007); https://doi.org/10.4324/9781849773799

34. Puy, A. et al. The delusive accuracy of global irrigation water withdrawal estimates. *Nat. Commun.* **13**, 3183 (2022).

35. Grafton, R. Q. et al. The paradox of irrigation efficiency. *Science* **361**, 748–750 (2018).

36. Jägermeyr, J. et al. Water savings potentials of irrigation systems: global simulation of processes and linkages. *Hydrol. Earth Syst. Sci.* **19**, 3073–3091 (2015).

37. Turner, S. W. D., Hejazi, M., Yonkofski, C., Kim, S. H. & Kyle, P. Influence of groundwater extraction costs and resource depletion limits on simulated global nonrenewable water withdrawals over the twenty-first century. *Earths Future* **7**, 123–135 (2019).

38. Bosch, H. J. & Gupta, J. Water property rights in investor-state contracts on extractive activities, affects water governance: an empirical assessment of 80 contracts in Africa and Asia. *Rev. Eur. Comp. Int. Environ. Law* **31**, 295–316 (2022).

39. Döll, P. et al. Impact of water withdrawals from groundwater and surface water on continental water storage variations. *J. Geodyn.* **59–60**, 143–156 (2012).

40. Gleeson, T. & Richter, B. How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers. *River Res. Appl.* **34**, 83–92 (2018).

41. Sun, J. X. et al. Review on research status of virtual water: the perspective of accounting methods, impact assessment and limitations. *Agric. Water Manag.* **243**, 106407 (2021).

42. Porkka, M., Guillaume, J. H. A., Siebert, S., Schaphoff, S. & Kummu, M. The use of food imports to overcome local limits to growth. *Earths Future* **5**, 393–407 (2017).

43. Wu, X. D. et al. Global socio-hydrology: an overview of virtual water use by the world economy from source of exploitation to sink of final consumption. *J. Hydrol.* **573**, 794–810 (2019).

44. Rosa, L., Chiarelli, D. D., Tu, C., Rulli, M. C. & D'Odorico, P. Global unsustainable virtual water flows in agricultural trade. *Environ. Res. Lett.* **14**, 114001 (2019).

45. Konar, M., Reimer, J. J., Hussein, Z. & Hanasaki, N. The water footprint of staple crop trade under climate and policy scenarios. *Environ. Res. Lett.* **11**, 35006 (2016).

46. Bai, X. et al. How to stop cities and companies causing planetary harm. *Nature* **609**, 463–466 (2022).

47. Ferguson, B. C., Frantzeskaki, N. & Brown, R. R. A strategic program for transitioning to a water sensitive city. *Landsc. Urban Plan.* **117**, 32–45 (2013).

48. Ye, Q. et al. Optimal allocation of physical water resources integrated with virtual water trade in water scarce regions: a case study for Beijing, China. *Water Res.* **129**, 264–276 (2018).

49. Arantes, C. C., Fitzgerald, D. B., Hoeinghaus, D. J. & Winemiller, K. O. Impacts of hydroelectric dams on fishes and fisheries in tropical rivers through the lens of functional traits. *Curr. Opin. Environ. Sustain.* **37**, 28–40 (2019).

50. *The What, Why and How of the World Water Crisis: Global Commission on the Economics of Water, Phase 1 Review and Findings* (GCEW, 2023).

51. Howard, G. et al. *Domestic Water Quantity, Service Level and Health* (WHO, 2020); apps.who.int/iris/bitstream/handle/10665/338044/9789240015241-eng.pdf

52. Gridded population of the world, version 4 (GPWv4): population density, revision 11. Center for International Earth Science Information Network, C.C.U. https://doi.org/10.7927/H49C6VHW (2018).

53. Wisser, D., Fekete, B. M., Vörösmarty, C. J. & Schumann, A. H. Reconstructing 20th century global hydrography: a contribution to the Global Terrestrial Network—Hydrology (GTN-H). *Hydrol. Earth Syst. Sci.* **14**, 1–24 (2010).

54. Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A. & Hegewisch, K. C. TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Sci. Data* **5**, 170191 (2018).

55. Zhang, Y. et al. A climate data record (CDR) for the global terrestrial water budget: 1984–2010. *Hydrol. Earth Syst. Sci.* **22**, 241–263 (2018).

56. Recknagel, T. et al. Global freshwater fluxes into the world oceans. *EGU General Assembly 2021* https://doi.org/10.5194/egusphere-egu21-16080 (2021).

57. Fekete, B. M., Vörösmarty, C. J. & Lammers, R. B. Scaling gridded river networks for macroscale hydrology: development, analysis, and control of error. *Water Resour. Res.* **37**, 1955–1967 (2001).

58. Major river basins of the world, 2nd rev. ext. ed. *GRDC* www.bafg.de/GRDC/EN/02_srvcs/22_gslrs/221_MRB/riverbasins.html (2020).

59. Rodell, M. & Famiglietti, J. S. The potential for satellite-based monitoring of groundwater storage changes using GRACE: the High Plains aquifer, Central US. *J. Hydrol.* **263**, 245–256 (2002).

60. Richey, A. S. et al. Quantifying renewable groundwater stress with GRACE. *Water Resour. Res.* **51**, 5217–5238 (2015).

61. Beaudoing, H. & M. Rodell, NASA/GSFC/HSL. GLDAS Noah Land Surface Model L4 3 hourly 0.25 × 0.25 degree V2.1 https://doi.org/10.5067/E7TYRXPJKWOQ (GES DISC, 2020).

62. Ferreira, V. G. et al. Characterization of the hydro-geological regime of Yangtze River basin using remotely-sensed and modeled products. *Sci. Total Environ.* **718**, 137354 (2020).

63. Agutu, N. O., Awange, J. L., Ndehedehe, C., Kirimi, F. & Kuhn, M. GRACE-derived groundwater changes over Greater Horn of Africa: temporal variability and the potential for irrigated agriculture. *Sci. Total Environ.* **693**, 133467 (2019).

64. Döll, P., Kaspar, F. & Lehner, B. A global hydrological model for deriving water availability indicators: model tuning and validation. *J. Hydrol.* **270**, 105–134 (2003).

65. Ojha, C., Werth, S. & Shirzaei, M. Groundwater loss and aquifer system compaction in San Joaquin Valley during 2012–2015 drought. *J. Geophys. Res. Solid Earth* **124**, 3127–3143 (2019).

66. Thomas, B. F. & Famiglietti, J. S. Identifying climate-induced groundwater depletion in GRACE observations. *Sci. Rep.* **9**, 4124 (2019).

67. Watkins, M. M., Wiese, D. N., Yuan, D.-N., Boening, C. & Landerer, F. W. Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons. *J. Geophys. Res. Solid Earth* **120**, 2648–2671 (2015).

68. Moeck, C. et al. A global-scale dataset of direct natural groundwater recharge rates: a review of variables, processes and relationships. *Sci. Total Environ.* **717**, 137042 (2020).

69. Schneider, U. et al. GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle. *Theor. Appl. Climatol.* **115**, 15–40 (2014).

70. Cartwright, I. & Irivine, D. The spatial extent and timescales of bank infiltration and return flows in an upland river system: implications for water quality and volumes. *Sci. Total Environ.* **743**, 140748 (2020).

71. De Graaf, I. E. M., van Beek, L. P. H., Wada, Y. & Bierkens, M. F. P. Dynamic attribution of global water demand to surface water and groundwater resources: effects of abstractions and return flows on river discharges. *Adv. Water Resour.* **64**, 21–33 (2014).

72. Rolls, R. J. & Bond, N. R. in *Water for the Environment: from Policy and Science to Implementation and Management* (eds Horn, A. C. et al.) 65–82 (Academic Press, 2017); https://doi.org/10.1016/B978-0-12-803907-6.00004-8

73. Rolls, R. J., Leigh, C. & Sheldon, F. Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. *Freshw. Sci.* **31**, 1163–1186 (2012).

74. García-Garizábal, I. & Causapé, J. Influence of irrigation water management on the quantity and quality of irrigation return flows. *J. Hydrol.* **385**, 36–43 (2010).

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Author contributions

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Competing interests

The authors declare no competing interests.

Additional information

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Reporting Summary

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Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Custom code written in Matlab version R2018A was used to generate the groundwater data in the study underpinned by the Mapping and Aerospace Tool boxes. Custom code written in Python version 3.9.7 was used to generate the surface water hydrology and population data.
Data analysis	Custom code in Python version 3.9.7, Matlab version R2018A and R version 4.2.1 was used to analyse the data in the study along with Microsoft Excel 365 to summarise the data and QGIS version 3.28.8 for mapping. The code for the groundwater recharge, rainfall, and groundwater data processing in this manuscript is available at https://doi.org/10.5281/zenodo.8361529. The code for surface water hydrology data processing in this manuscript is available at https://doi.org/10.5281/zenodo.8343035.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The groundwater data were derived from the Gravity Recovery And Climate Experiment (http://www2.csr.utexas.edu/grace/RL06_mascons.html) and the Global Land Data Assimilation System (https://disc.gsfc.nasa.gov/datacollection/GLDAS_NOAH025_3H_2.1.html). Annual rainfall data come from the Global Precipitation Climatology Centre (GPCC) precipitation data (mm) available at https://psl.noaa.gov/data/gridded/data.gpcc.html. The data for the surface water hydrology were derived from existing published datasets cited in the manuscript.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	N/A
Population characteristics	N/A
Recruitment	N/A
Ethics oversight	N/A

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Global spatial analysis of river basins in the context of the safe and just Earth system boundaries. No formal statistical analyses were undertaken, but rather quantification of populations in each river basin inside and outside the earth system boundaries. The approach is fully described in the Methods section.
Research sample	Global scale river basin analysis, which is the scale of the sub-global Earth system boundaries.
Sampling strategy	No sample size calculation was performed. The unit of observation, whole river basins, was used as it is the relevant scale for the sub-global Earth system boundaries.
Data collection	Surface water hydrology were generated by Pamela Green who extracted data from the WBM Water Balance Model. Groundwater hydrology data were generated by Christopher Ndehedehe who extracted the relevant data from the GRACE satellite and the GLDAS hydrology models.
Timing and spatial scale	The timing of the surface water hydrology data was monthly 2000-2020 (summarised to the annual timestep) and monthly from 2003-2016 for the GRACE data. The surface water hydrology data was generated on a digital river network with pixels at the 6 arc-minute scale. The groundwater data was generated at a quarter degree scale. These data were then summarised to the river basin scale as described in the Methods.
Data exclusions	No data were excluded.
Reproducibility	The underlying source data were compared with other available data sources in the paper by Rockstrom et al. 2023, https://doi.org/10.1038/s41586-023-06083-8.
Randomization	N/A
Blinding	N/A

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒ ☐	Antibodies
☒ ☐	Eukaryotic cell lines
☒ ☐	Palaeontology and archaeology
☒ ☐	Animals and other organisms
☒ ☐	Clinical data
☒ ☐	Dual use research of concern

Methods

n/a	Involved in the study
☒ ☐	ChIP-seq
☒ ☐	Flow cytometry
☒ ☐	MRI-based neuroimaging