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Human domination of the global water cycle absent from depictions and perceptions

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Human water use, climate change and land conversion have created a water crisis for billions of individuals and many ecosystems worldwide. Global water stocks and fluxes are estimated empirically and with computer models, but this information is conveyed to policymakers and researchers through water cycle diagrams. Here we compiled a synthesis of the global water cycle, which we compared with 464 water cycle diagrams from around the world. Although human freshwater appropriation now equals half of global river discharge, only 15% of the water cycle diagrams depicted human interaction with water. Only 2% of the diagrams showed climate change or water pollution—two of the central causes of the global water crisis—which effectively conveys a false sense of water security. A single catchment was depicted in 95% of the diagrams, which precludes the representation of teleconnections such as ocean–land interactions and continental moisture recycling. These inaccuracies correspond with specific dimensions of water mismanagement, which suggest that flaws in water diagrams reflect and reinforce the misunderstanding of global hydrology by policymakers, researchers and the public. Correct depictions of the water cycle will not solve the global water crisis, but reconceiving this symbol is an important step towards equitable water governance, sustainable development and planetary thinking in the Anthropocene.

The water cycle is one of the first great cycles with which many people engage during their basic education[1,2]. In the absence of direct experience with large-scale hydrological processes, these diagrams form the basis of our valuation and management of the global water cycle[3–6]. Although water cycle diagrams may not be intended as comprehensive representations of the entirety of hydrological science, they effectively play this role for many educators, policymakers and researchers, which increases the societal stakes of systematic inaccuracies. Diagrams of the global water cycle explicitly and implicitly teach core scientific principles, which include the conservation of mass, the reality that human activity can cause global-scale changes and the concept that distant processes can have acute, local effects. Flaws in this pedagogic tool could therefore undermine efforts to promote an understanding of water and also of general scientific thinking[1,7,8]. As humans now dominate critical components of the hydrosphere[9–11], and 80% of the world's population faces water insecurity or severe water scarcity[12,13], improving our understanding of the global water cycle has graduated from an academic exercise to a planetary priority.

Human activity alters the water cycle in three distinct but interrelated ways. First, humans appropriate water through the livestock, crop and forestry use of soil moisture (green water use), water withdrawals (blue water use) and water required to assimilate pollution (grey water use (Fig. 1 and Supplementary Table 1))[10,11,14,15]. Second, humans have disturbed approximately three-quarters of the Earth's ice-free land surface through activities that include agriculture, deforestation and wetland destruction[16]. These disturbances alter evapotranspiration, groundwater recharge, river discharge and precipitation at continental scales[17–19]. Third, climate change is disrupting patterns of water flow and storage at local to global scales[20–22]. These human interferences with the water cycle have confounded efforts to model regional and global water circulation[18,23,24]. More importantly, human activity has created a constellation of water crises that threaten billions of people and many ecosystems worldwide[12,18,25–27]. These regional crises of water quality, quantity and timing have become global because they affect such a large portion of the Earth's human population and ecosystems, and because they are increasingly driven by large-scale climate change, land use

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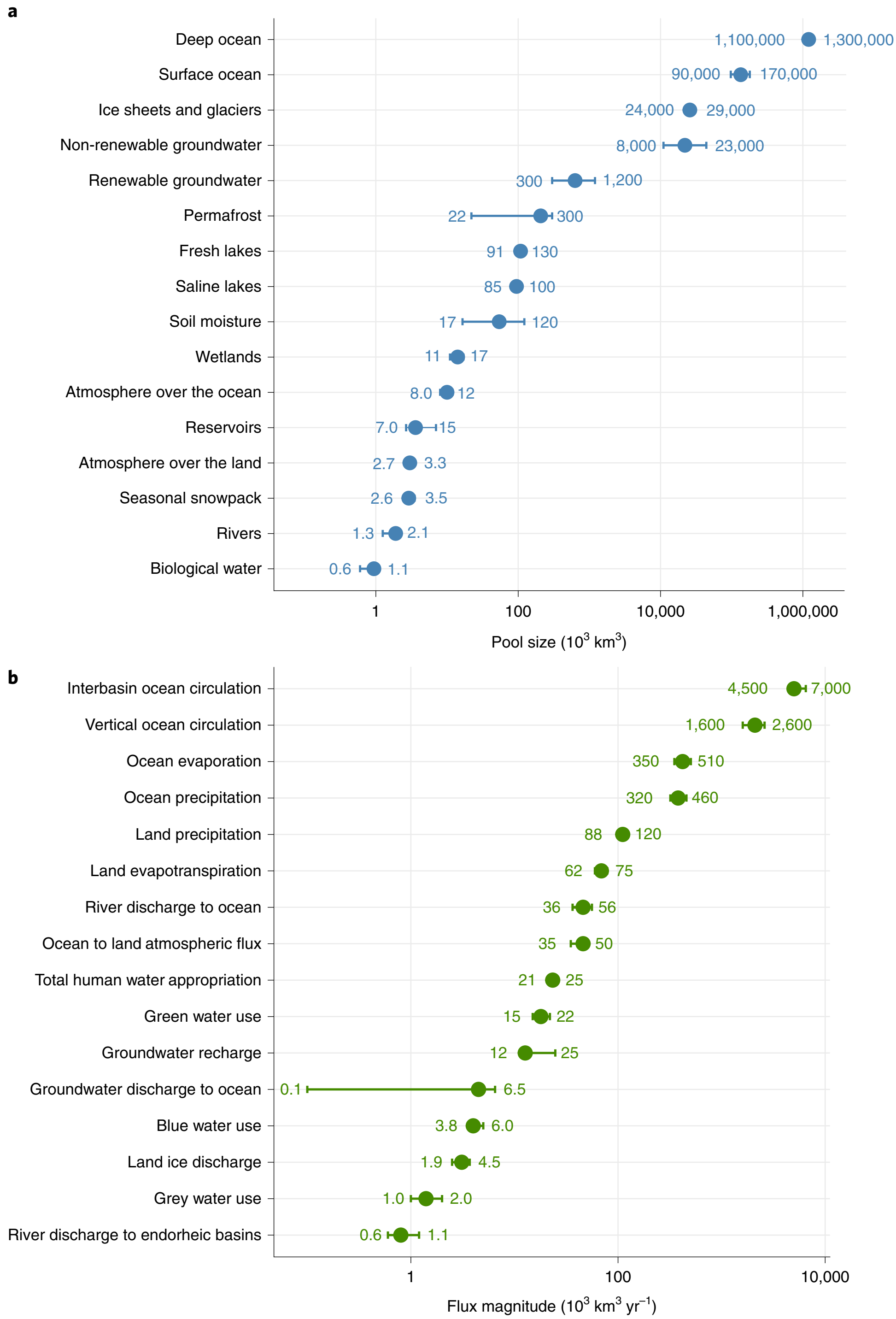

Fig. 1 | Pools and fluxes in the global hydrological cycle. a,**b**, Estimates of major pools (**a**) and fluxes (**b**) are based on a synthesis of ~80 recent regional- and global-scale studies (Supplementary Table 1). The central point represents the most recent or comprehensive individual estimate, and error bars represent the range of reported values and their uncertainties. Note the log scales on the *x* axes.

and teleconnections between water use and water availability that extend beyond the boundaries of individual catchments[17,19,28].

As the global water crisis is defined by human beliefs about society and nature[29–32], we investigated how different research disciplines and countries conceptualize the water cycle by analysing their representations of it. We hypothesized that diverse worldviews and scientific approaches among disciplines and countries would influence the focus, detail and comprehensiveness of the diagrams. We also hypothesized that advances in global hydrology[9,33,34] and concerted efforts to better integrate humans into our mental models of the water cycle[5,6,30] would improve the diagrams through time. To test these hypotheses, we compiled estimates of global water pools and fluxes from more than 80 recent modelling and empirical studies, which included multiple dimensions of human water use (Fig. 1 and Supplementary Table 1). We then collected 114 English-language diagrams of the water cycle from textbooks, peer-reviewed articles, government materials and online sources (Methods). For each diagram, we quantified detailed metrics, including the biome,

Table 1 | Percentage of diagrams that showed water pools, fluxes and human activity

Water pools ($n=114$)	%	Water fluxes ($n=114$)	%
Atmosphere over the land	94	Land precipitation	99
Ocean	93	Condensation	88
Renewable groundwater	81	Land evapotranspiration	87
Rivers	77	Ocean evaporation	85
Atmosphere over the ocean	73	River discharge to ocean	75
Fresh lakes	64	Ocean to land atmospheric flux	74
Ice sheets and glaciers	53	Subsurface flow	73
Soil moisture	41	Surface runoff	62
Seasonal snowpack	26	Infiltration	50
Biological water	25	Groundwater recharge	49
Reservoirs	11	Groundwater discharge to ocean	47
Wetlands	10	Ocean precipitation	42
Non-renewable groundwater	8	Snow	33
Permafrost	5	Snowmelt	17
Fauna	4	Interception	11
Dew	2	Ocean circulation	7
Intermittent rivers	1	Sublimation	7
Saline lakes	0	Springs	6
Human activity ($n=464$)	**%**	Volcanic steam	3
Any sign of humans	23	Deposition	2
Humans integrated with water cycle	15	River discharge to endorheic basins	2
Blue water use	10	Ice discharge	1
Green water use	3	Water loss to space	1
Grey water use (pollution)	2	Water capture from space	1
Climate change	1.4	Fog	1

scientific fields and the number, magnitude and ratios of water pools and fluxes, which we compared to our global water cycle synthesis. To analyse the depiction of humans in the diagrams most accessed by the public, we then collected 350 diagrams from 12 countries using Internet image searches in the local language.

Reality and representation of global water pools and fluxes

Our synthesis of recent water cycle studies revealed large revisions of many pool and flux estimates over the past decade, attributable to advances in remote sensing, modelling and regional to national accounting (Fig. 1 and Supplementary Table 1). Perhaps most notably, new estimates of human green, blue and grey water use now total ~24,000 $km^3 yr^{-1}$ (Fig. 1 and Supplementary Table 1)[10,11,14,15]. This means that human freshwater appropriation redistributes the equivalent of half of global river discharge or double global groundwater recharge each year. Compared with water cycle syntheses from a decade ago[30,35], recent estimates were higher for artificial reservoir storage[36], non-renewable groundwater[33] and groundwater recharge[37], but were lower for sustainably available freshwater[10,14,15], renewable groundwater[9,33,38] and endorheic lakes[27,39]. Substantial uncertainty persisted for several pools and fluxes critical to societal and ecological water needs, including groundwater, soil moisture, water in permafrost and groundwater discharge to the ocean (Fig. 1 and Supplementary Table 1).

Despite diversity across disciplines and countries, the water cycle diagrams were remarkably consistent in graphical layout. Two-thirds of the diagrams showed water flowing from left to right, and only four distinct formats appeared in the whole sample (Supplementary Fig. 1). There were abundant commonalities in details such as placement of landscape components and elements of the water cycle, which suggest common lineage and copying (Supplementary Table 3). Sixteen unique water pools and 27 unique water fluxes appeared in at least one of the 114 diagrams analysed in detail (Table 1). With the notable exception of saline lakes, the largest 16 water pools and fluxes from our synthesis of the water cycle (Fig. 1) were depicted in at least one of the diagrams (Table 1 and Fig. 2). However, pool size did not influence the likelihood of inclusion, with five of the ten largest water pools depicted in 50% or less of the diagrams (non-renewable groundwater, permafrost, saline lakes, wetlands and soil moisture (Table 1 and Fig. 2a)). The depiction of water fluxes was generally more representative of reality, with the notable exceptions of the largest global water flux, ocean circulation, which appeared in only 8% of the diagrams, and the third largest flux, precipitation over the ocean, which appeared in 42% (Table 1 and Fig. 2b).

We found little support for our hypotheses that diagrams would differ by audience and vary through time (Fig. 2 and Supplementary Table 3). Patterns in the prevalence of pools and fluxes were similar for scientific and public diagrams (Supplementary Figs. 2–5) and there were even fewer differences through time; only one pool and four fluxes showed more than a 10 percentage point difference for diagrams made before and after January 1 2006—the chosen cutoff to separate older from newer diagrams (Fig. 2).

Landscapes devoid of humans with abundant water

Several widespread biases in water diagrams were apparent in our analysis, including under-representation of precipitation over the ocean (74% of diagrams), over-representation of temperate ecosystems from the Northern Hemisphere (92% of diagrams), exclusive focus on single-catchment dynamics (95% of diagrams), and no representation of uncertainty (99% of diagrams) (Supplementary Figs. 1–5). Perhaps most surprisingly, 85% of the diagrams showed no interaction between humans and the water cycle. There were strong national differences in human representation—approximately 25% of the French and German diagrams integrated human activity with the water cycle, but less than 5% of the Chinese, United States and Australian diagrams did so (Table 2). The originating discipline also influenced the depiction of human–water interactions, which appeared in approximately one-third of the diagrams from hydrology, natural sciences and meteorology, but in less than 15% of the diagrams from the fields of land management, geography and oceanography (Supplementary Fig. 4). The representation of grey water use and climate-mediated interference with the water cycle was extremely rare across disciplines and countries, with water pollution depicted in only 2% of the diagrams and the effects of climate change represented in only 1.4% of the diagrams (Table 1). Green water use, which constitutes ~78% of total human water appropriation, was only shown in 3% of the diagrams. Contrary to our expectation, newer diagrams were less likely to integrate humans compared to those created before 2006 (16 versus 22%, respectively (Fig. 2)).

Water diagrams implicitly and explicitly overrepresented the freshwater available for human use in three ways. First, as the diagrams did not distinguish saline from freshwater lakes and renewable from non-renewable groundwater, they did not communicate that half of the global lake volume is saline[27,33,39,40] and that approximately 97% of the groundwater is non-renewable on centennial timescales (insufficient recharge or not suitable for human use due to a high salinity)[23,25,33,41] (Fig. 3). Even quantitative diagrams typically reported the sum volume of these pools (for example, 190,000 km^3 for lakes and 22,600,000 km^3 for groundwater), which grossly overrepresented the actual freshwater stocks. This overrepresentation is even more severe in the light of recent evidence that the renewable groundwater

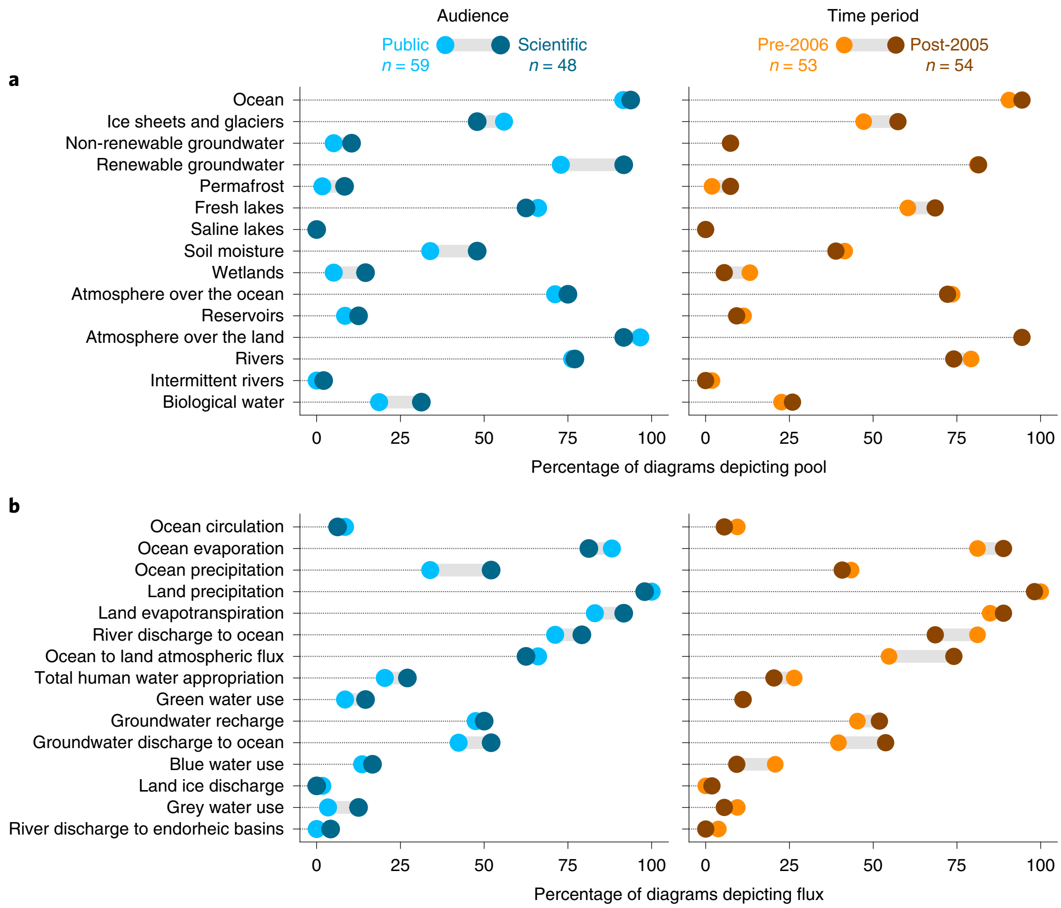

Fig. 2 | Pools and fluxes represented in water cycle diagrams. a,b, Percentage of water cycle diagrams that represent major pools (**a**) and fluxes (**b**) in the global water cycle. Pools and fluxes are ordered by size based on Fig. 1, starting with the largest pool (ocean) and flux (ocean circulation). We categorized diagrams by intended audience and time period. Public diagrams include those made for advertising, advocacy, government outreach and primary or secondary education, whereas scientific diagrams were made for higher education textbooks and peer-reviewed publications. We compared the diagrams made before and after 1 January 2006, which corresponds with the publishing of several high-profile papers that advocated increased integration of social and hydrological systems. The grey bar between points is visible for differences greater than 10 percentage points.

Table 2 | National differences in the representation of human activity in 380 water cycle diagrams

Country	Search language	Any sign of humans	Integrated with water cycle	Green water use	Blue water use	Grey water use (pollution)	Climate change	Overlap with main sample[a]
France	French	43	27	0	20	0	0	10
Germany	German	47	23	0	23	0	0	20
Romania	Romanian	27	20	0	7	3	3	23
Tunisia	Arabic	27	17	0	10	3	3	20
India	Hindi	20	17	0	10	0	0	23
Brazil	Portuguese	30	13	3	7	0	0	7
Russia	Russian	27	10	0	13	0	0	13
Mexico	Spanish	10	10	0	0	0	0	20
South Africa	English	7	7	0	7	0	0	73
China	Mandarin	4	4	2	2	0	0	7
USA	English	7	3	0	3	0	0	100
Australia	English	0	0	0	0	0	0	77

All the values are in percentage and $n=30$ for all the countries except China, for which $n=50$. The table is ordered by the percentage of diagrams that integrate humans with the water cycle. We analysed water cycle diagrams that were obtained from online image searches of the term ‘water cycle’ or its translation for 12 countries. Searches were performed on Baidu.com for China and Google.com for all the other countries. [a]Percentage of diagrams from the country-specific image search that also occurred in the sample of 114 water cycle diagrams analysed for the whole suite of characteristics.

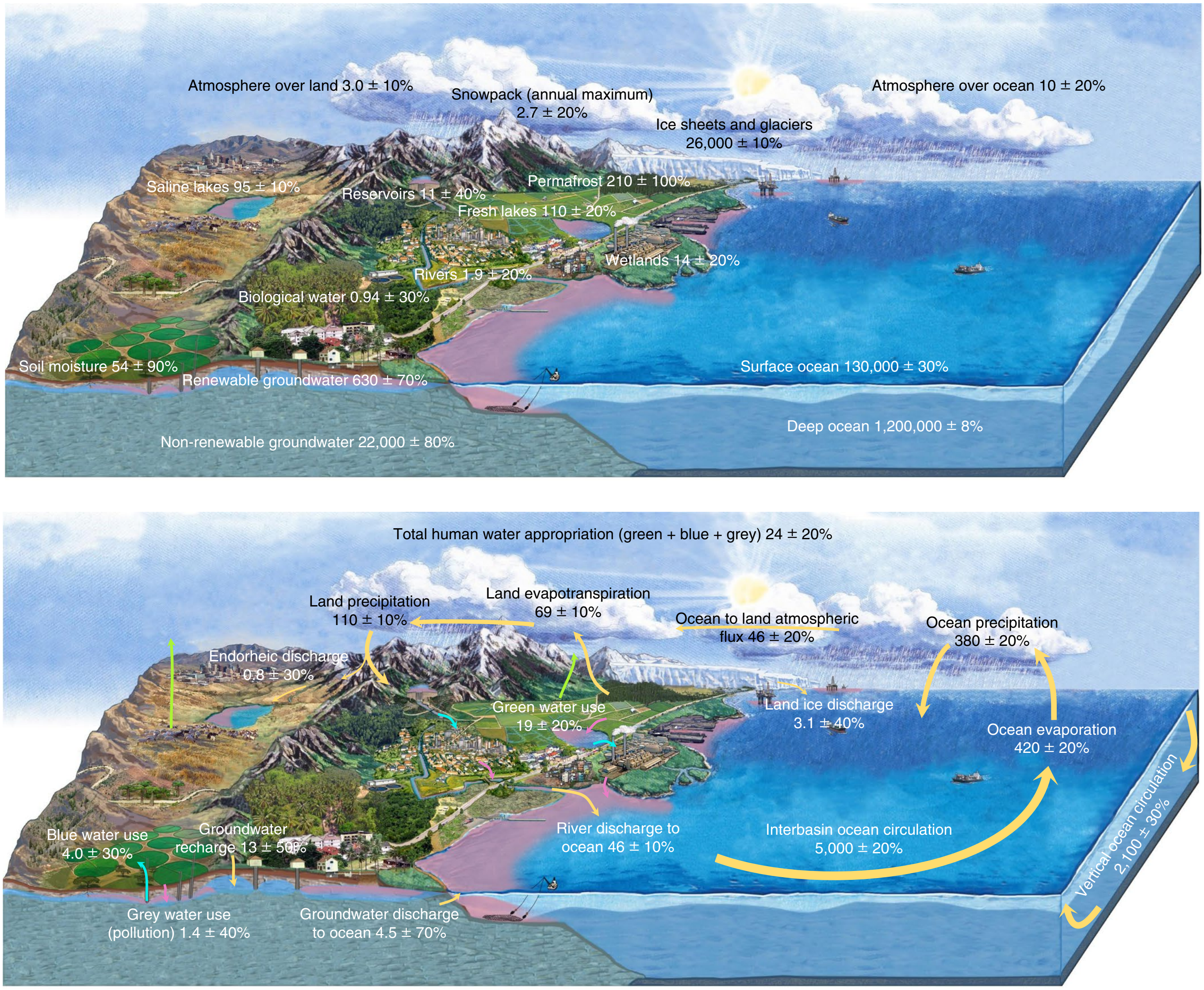

Fig. 3 | Diagram of the global hydrological cycle in the Anthropocene. a,**b**, Major water pools (expressed in 10^3 km^3) (**a**) and water fluxes (expressed in 10^3 km^3 yr^{-1}) (**b**). Uncertainty represents the range of recent estimates expressed in %. In **b**, we separate total human water use (~24 10^3 km^3 yr^{-1}) into green (soil moisture used by human crops and rangelands, green arrows); blue (consumptive water use by agriculture, industry and domestic activity, blue arrows); and grey (water necessary to dilute human pollutants, which is represented with pink shading, pink arrows). This averaged depiction of the hydrological cycle does not represent important seasonal and interannual variation in many pools and fluxes.

volume in many regions is less than half the historic estimates, which were often based on first-order measurements or extrapolations[9,33]. Second, no diagrams indicated the proportions of pools and flows that are accessible for human use. Less than 10% of annual terrestrial precipitation and 25% of annual river flow are sustainably available for human consumptive use[30], and only 1–5% of fresh groundwater is sustainably extractable[9,41]. This means that globally accessible and sustainable blue water probably ranges from 5,000 to 9,000 km^3 yr^{-1} (refs. [10,14]), which is alarmingly close to the current estimates of global consumptive water use, which range from 3,800 to 5,000 km^3 yr^{-1} (Supplementary Table 1)[11,21,42,43]. Third, by excluding grey water use (water pollution), the diagrams did not communicate that human activity has further diminished the small fraction of accessible and sustainable freshwater by 30 to 50% (refs. [11,13,14]).

Why are diagrams still so wrong and does it matter?

Diagrams of the water cycle are the central icon of hydrological sciences and one of the most visible and widespread scientific symbols in any field. These diagrams both influence and represent the understanding of researchers, educators and policymakers[8,31,44], which shapes how society relates to water[6,29,45]. Their high profile means that criticisms of water cycle diagrams are nearly as old as the diagrams themselves, dating at least to the 1930s when they became common[31,46] and continuing to the present[5]. In this context, two questions arise from our analysis. Why do so many fundamental errors in global water cycle diagrams persist, and do these errors contribute to mismanagement of water?

Several dynamics probably contribute to the stubborn persistence of water cycle inaccuracies. First, a practical challenge to creating an accessible and accurate representation of the water cycle is that it includes pools that vary in size by six orders of magnitude and fluxes that span five orders of magnitude (Figs. 1 and 3 and Supplementary Table 1). We recognize the inherent difficulty in creating an effective and attractive diagram that teaches core concepts in addition to communicating quantitative data[7]. Our purpose is not to nitpick the necessary simplifications and distortions associated with scientific

Fig. 4 | Some consequences of human interference with the water cycle. Although every aspect of the global hydrological cycle is influenced by a combination of climate change, land use and water use, we indicate a predominant cause by box color.

visualizations; we wish to highlight a pervasive absence and inaccuracy: the exclusion of humans and the overrepresentation of the water available for human use. Another contributing factor to the rarity of depicting human influence may be an aesthetic preference for natural landscapes. Proclivity for naturalness has both cultural and evolutionary roots, which could be reinforced by industrialization and urbanization[47–49] and so explain the absence of humans in the diagrams from some of the most developed and water-stressed countries in our sample (Table 2). However, online image searches for 'global carbon cycle' and 'global nitrogen cycle' reveal that 97% and 87% depict human activity, respectively (based on the first 30 results). This suggests that other dynamics, which include historical context, contribute to the absence of humans in water diagrams. Hydrology emerged as an independent scientific field of study in the United States in the 1930s, coincident with the popularization of modern water cycle diagrams[6,49]. Partly in an effort to establish hydrology as a natural science distinct from civil engineering and agronomy, these conceptual models both emphasized the natural components of the water cycle and minimized or excluded human activity[6,31]. Perhaps most fundamentally, large-scale anthropogenic effects on the water cycle were less extensive and less understood a century ago[18,34,50], which precluded the representation of land use affecting downwind catchments and other teleconnections[28,51]. Together, these practical, aesthetic and historical factors may have counteracted efforts to integrate humans into depictions of the water cycle[4,49].

On the second question of whether water cycle inaccuracies contribute to the mismanagement of water resources, four of the diagrammatic flaws we found here correspond directly with current failings in water management (Fig. 4). First, disregard of the hydrological teleconnections between oceans and continents and among catchments has led to attempts to solve water scarcity with single-catchment interventions. Such 'demand-side' approaches to water management include the manipulation of vegetation[3], construction of pipelines and dams[52], and cloud seeding[53]. If larger spatial scales are not considered, costly catchment interventions can exacerbate water scarcity and undermine other sustainable development goals by diverting the flow from downstream and downwind communities and reducing resilience to natural and anthropogenic variability[13,48,54]. Second, a lack of understanding of short- and long-term temporal change has led to the overallocation of water resources and overdependence on engineered water infrastructures[55–57]. Seasonal and interannual variability in available water is a hallmark of the hydrosphere, which will only increase with climate change[12,58]. However, 99% of the diagrams in our sample and many water regulatory frameworks worldwide assume that water resources are stable on seasonal to interannual timescales[5,10]. Disregard of the temporal variability means that groundwater is extracted faster than it is recharged at a global scale[9,23,25], terminal (endorheic) lakes and wetlands are in decline on every continent except Antarctica[27,39] and semi-arid regions are experiencing desertification[21,22]. Third, water quality and water quantity are often treated as separate issues due to technical, legal and disciplinary differences[52,59–61]. Although links between water flow and water chemistry have been understood for decades[62], efforts to increase water quantity routinely trigger the eutrophication of fresh and saltwater ecosystems[63,64], salinization[65] and ultimately reductions in useable water[14,27]. Fourth, much of current water management focuses on securing water supply rather than managing water demand[28,32]. This approach presumes that water scarcity is determined exclusively by climate and that human water use is effectively unchangeable[3,51,66]. Although these inaccuracies probably reflect as much as they reinforce bad water policy, depictions of abundant and pristine freshwater resources, so common in water cycle diagrams, belie the need for land conservation and water efficiency, which are critical to ensure societal and ecological water flows in a changing world[10,28,45].

A water cycle for the Anthropocene

The omission of humans and associated changes from water cycle diagrams is deeply problematic because it implies that one of our most essential and threatened resources is not influenced by our actions. The exclusion of humans obscures some of the most urgent socioecological crises, which include water security and water justice[10,28,49,51], the loss of aquatic biodiversity[13,26], climate change[20,24] and freshwater and coastal eutrophication[14,18]. Given the immense scale of human suffering and ecological destruction associated with the global water crisis, we need to bring to bear all our scientific and cultural faculties to increase understanding and accelerate the implementation of sustainable water management.

Beyond the obvious fixes of depicting human activity and distinguishing water that is sustainably available, several changes could substantially improve the ability of diagrams to communicate the critical concepts addressed in the previous section (Figs. 3 and 4). Although 95% of the diagrams in our sample showed a single catchment, using a multicatchment template allows the depiction of 'supply-side' water dynamics, in which water debits from one catchment are credits in the next via cross-continental atmospheric transport of water vapour[3,28,51]. This continental moisture recycling is the primary driver of terrestrial precipitation—150% larger than the ocean-to-land atmospheric flux (Fig. 3). A diagram with multiple catchments allows an intuitive understanding of water movement[67,68] as it communicates the nested interactions of a global water cycle made up of many small circuits, not a single great circle (Fig. 4). More specifically, with only a single catchment to draw on, it is not possible to depict inland endorheic basins, which are extremely vulnerable to direct human disturbance, upwind alteration of evapotranspiration and climatic shifts. The mismanagement of water in endorheic basins has caused some of the Earth's most serious ecological, economic and human health catastrophes[18,27,39], although these woes are neglected in water cycle diagrams, none of which depict endorheic lakes. Additionally, images that reflect local socioecological conditions (Fig. 4) are more likely to engage observers and provide actionable insight to water consumers and managers[5,69], and so enhance coalition building and cooperative action[44,70].

Another diagrammatic need is the representation of seasonal and interannual variability in water pools and fluxes. Temporal variability in the water cycle is poorly understood by the public[1,2]. However, change through time is indispensable to understanding hydrology because pools and fluxes, such as soil moisture, river discharge and precipitation vary by orders of magnitude on short-term, seasonal and interannual timescales. Additionally, concepts of water security and aquatic biodiversity are only comprehensible in a framework of temporal change because they are defined by short-term extremes (for example, droughts, floods and biogeochemical pulses), not long-term averages[12–14,61]. Conveying temporal change in water diagrams could be achieved through multipanel illustrations (insets or storyboards), labelled alternative states or ranges and implied motion through imbalance. Additionally, new formats allow the representation of temporal variability directly in animated or interactive diagrams, which have proved effective at catalysing deeper thinking about complex systems[71].

Finally, attention to aesthetics is perhaps as essential as any other water diagram improvement. Attractiveness will strongly influence the rate and degree of adoption among both educators and scientists. The same plagiarism we observed among current water cycle diagrams could facilitate a rapid and broad penetration of attractive and more accurate versions of the water cycle when introduced into the public domain.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of code and data availability and associated accession codes are available at https://doi.org/10.1038/s41561-019-0374-y.

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Author contributions
The concept for this paper emerged during discussion among B.W.A., K.B., G.P., T.K., D.M.H., S.K. and J.P.Z. in 2015. S.P., S.E.G., T.K., J.M., O.U., M.C., R.J.F., B.W.A. and M.B. downloaded and analysed the diagrams. B.W.A. and C.M. managed data and performed statistical analyses. B.W.A. wrote the manuscript with input from all the co-authors.

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The authors declare no competing interests.

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Methods

Diagram collection. To identify gaps in the general understanding of hydrology and implicit hypotheses held by water-related researchers, we compiled a new synthesis of the global water cycle (Supplementary Table 1) and analysed 464 diagrams of the water cycle. Initially, we collected 114 diagrams from textbooks, scientific articles, teaching materials, advertisements and agency reports, which we identified by querying Web of Science, Google Scholar and Google Books. To avoid bias in this selection, no representations of the water cycle were excluded. To assess diagrams most accessed by the public, we then collected the top 30 diagrams that appeared in an online image search for 'water cycle' in 12 countries translated into the local language, using the Baidu search engine for China, and Google for all other countries (Table 2 and further details below).

Visual analysis. For the initial sample of 114 diagrams published in English, we extracted 52 parameters based on the visual representation of the water cycle (Supplementary Database 1). This detailed analysis included continuous ratios of five parameters: the percentage of total horizontal visual space occupied by the ocean, the percentage of the total precipitation and evaporation that occurred on land, the ratio of the overall evapotranspiration to precipitation and the ratio of terrestrial evapotranspiration to ocean to land atmospheric water transport. We also quantified the presence or absence of 17 water pools and 27 water fluxes (Table 1), signs of human activity (for example, buildings, fields, livestock and people), the integration of humans in the water cycle (for example, green, blue or grey water use), and representation of climate change.

For the 114 English-language diagrams, we additionally determined ten classifying parameters about each diagram and its producer (the person or group that created it). The diagram parameters were: the date of creation, whether the water pools and fluxes were represented qualitatively or quantitatively, diagram format (catchment, hillslope, site or schematic (Supplementary Fig. 1)), dimensionality of the drawing (two- or three-dimensional (2D or 3D), biome type represented (for example, Arctic, boreal, temperate, tropical or desert) and publication type (article, textbook or online). The producer parameters were: producer type, which indicates whether the diagram was created by researchers for peer-reviewed articles or reports (research), by a governmental agency (government), for use in higher education (academic), for use in primary or secondary education (education), for use in advertising or for advocacy purposes; whether the diagram was intended for a scientific audience (articles, reports or college textbooks) or a public audience (advocacy or advertising); and scientific discipline for the research and academic diagrams. As the sample size for some disciplines was limited, we grouped agronomy, forestry and soil science into a land management category, and ecosystem ecology, biogeochemistry, aquatic ecology and geology into a natural sciences category. For all the disciplinary classifications, we considered first the publication outlet, followed by the primary research discipline of the lead author and finally her or his departmental affiliation. To test for changes through time, we split the data set into diagrams created before and after 1 January 2006, which corresponds with the publication of several high-profile papers that advocated a better integration of humans into conceptualizations of the water cycle[6,30,72,73]. This separation also provided relatively balanced sample sizes between the two periods.

For both the initial sample of English-language diagrams and for the international comparison described below, we ensured a consistency in data extraction by analysing every diagram at least twice (that is, two different researchers extracted data from the diagrams independently) and the lead author performed a final verification of every diagram and associated data.

International comparison. To test if the patterns observed in our initial sample of technical English-language diagrams held for non-technical diagrams, we analysed the human representation in an additional set of 350 online images from 12 countries (Table 2 and Supplementary Table 2). We systematically collected the most-accessed 30 diagrams for 12 countries by performing an online image search for 'water cycle' translated into the local language, using the Baidu search engine for China and Google for all other countries. As for the set of initial diagrams, we did not exclude any images of the water cycle, to avoid potential sampling bias.

As many identical or similar diagrams appeared in the data set, we created an automated image-comparison algorithm to identify duplicate diagrams. We converted each diagram into greyscale, with each pixel associated with a value of grey from 1 to 256, and then computed the statistical distribution of grey levels for all the pixels contained in each image, normalized according to the image size. To find the potential matches for one diagram, correlation coefficients of cumulative greyscale pixel distribution plots were calculated. The algorithm selected the top ten potentially similar items that corresponded to the ten highest correlation coefficients; we the identified true duplication manually.

We calculated summary statistics and produced visualizations with R version 3.3.0 using the ggplot2 package[74].

Detailed analysis of water cycle diagrams. Water cycle diagrams were remarkably consistent in graphical layout—two-thirds of the diagrams showed water flowing from left to right, and only four distinct formats appeared in the whole sample (Supplementary Fig. 1). Of the diagrams with an identifiable biome, 92% depicted temperate ecosystems, 5% showed boreal ecosystems, 2% showed arid ecosystems and 1% depicted multiple biomes. Only 5% of the diagrams showed more than a single catchment, which effectively precluded representation of endorheic (internally draining) basins and anthropogenic or natural interbasin water transport. There were abundant commonalities in the details, such as the placement of the landscape components and elements of the water cycle, which suggested widespread copying. This was particularly true for diagrams found through online image searches, where many images were slight modifications of material from textbooks, government outreach or research articles (Supplementary Table 3). Most diagrams were qualitative and only 18% included quantitative estimates of pool sizes and flux magnitudes.

There were only minor differences in the number of pools and fluxes in the diagrams produced by different sectors (for example, government, education and advertising) or research disciplines, but the detail did vary by diagram format and type, as catchment-scale diagrams and newer quantitative diagrams showed significantly more pools and fluxes, based on comparisons of the 95% confidence intervals of medians (Supplementary Figs. 3 and 5). Diagrams from different disciplines generally showed the same patterns in percentage representation of individual pools and fluxes (mean of pairwise Pearson's $r=0.88$ (Supplementary Fig. 4 and Supplementary Table 3)), although natural sciences (that is, ecology, biogeochemistry and geology) were distinct from oceanography ($r=0.65$) and, to a lesser extent, from meteorology ($r=0.76$ (Supplementary Table 3)).

Across sectors and disciplines, only 26% of the diagrams showed ratios of ocean and land precipitation that agreed with the benchmark (that is, 3.2–3.7 (Supplementary Fig. 2)). There was no ocean precipitation at all in 58% of the diagrams, an additional 27% had approximately equal precipitation over the ocean and land and only 2% over-represented ocean precipitation (Supplementary Fig. 2b). There was a split between quantitative diagrams, which usually fell within the benchmark ocean-to-land precipitation ratios, and qualitative diagrams, which did not, which explained the more accurate performance of schematic diagrams, as 70% were quantitative (Supplementary Fig. 5). The same general patterns held for ocean and land evapotranspiration, as 27% of models fell in the benchmark range (that is, 6.1–6.5), 65% showed equal or less evaporation from the ocean than the land and only 8% over-represented ocean evaporation (Supplementary Fig. 2). Just over one-third of the diagrams (36%) agreed with the benchmark estimates of the ratio of terrestrial evapotranspiration to atmospheric flux from the ocean (that is, 1.2–2.1; this is an index of the proximate source of the terrestrial precipitation[3]), 51% fell below the benchmark range and 13% were above it (Supplementary Figs. 2 and 5). The ratios of total evapotranspiration and precipitation were more accurate, but still skewed as 63% of all the diagrams fell around parity, 8% showed too little evapotranspiration and 29% showed more evapotranspiration than precipitation (Supplementary Figs. 2 and 5).

Although we hypothesized that the accuracy of the diagrams would improve through time due to advances in global hydrology and concerted efforts to better integrate humans into depictions of the water cycle[6,30,75], newer diagrams were actually less likely to integrate humans compared to those created before 2006 (16 versus 22%, respectively (Fig. 2)). The frequency of human representation did change with diagram format, with 3D catchment format diagrams showing humans interacting with water 35% of the time, but only 9% of hillslope, schematic, and site format diagrams doing so (Supplementary Fig. 1). The 'catchment' format diagrams are large-scale, 3D (upper left in Supplementary Fig. 1) 'hillslope' diagrams are small scale, 2D (upper right) 'site' diagrams integrate aspects of catchment and hillslope diagrams (lower left) and 'schematic' diagrams are the most abstract representations as they typically consist of boxes and arrows (lower right).

Recommendations to improve water cycle diagrams. Although a true proportional representation of water cycle pools and fluxes may not be possible or desirable (for example, to show the ocean one million times larger than rivers), creators of water diagrams should be aware of the relative magnitudes of fluxes and pools, which allows deliberate divergences in any specific presentation[2]. In our sample, quantitative diagrams were more accurate than non-quantitative diagrams in all the dimensions we measured, which demonstrates the effectiveness of multimodal representations using both visual and numerical abstractions of the water cycle. However, to assign a single number to a flux or pool may undermine the depiction of temporal change and imply a lack of uncertainty[5]. Visual and numerical estimates should be accompanied by uncertainty ranges[59], particularly when poorly constrained fluxes and pools are represented, such as groundwater, human-available water, permafrost water and human effects on evapotranspiration (Fig. 1)[9,33,54,76].

To convey temporal change could be achieved by including multipanel illustrations (insets or storyboards), labelled alternative states or ranges and implied motion through imbalance[5,77]. It is also possible to depict temporal change explicitly with animated and interactive models. Gamification, virtual reality and augmented reality approaches can be effective at catalysing systems thinking about the water cycle[71].

Finally, attention to aesthetics is perhaps as essential as any other water diagram improvement. Attractiveness strongly influences the rate and degree of adoption among both educators and scientists. One of the reasons some of the more accurate diagrams have not become widespread may be that currently most diagrams that integrate humans are not as artistic or professional as those that show natural landscapes. The same plagiarism or sharing that is apparent among the current water cycle diagrams could facilitate the rapid and broad penetration of attractive and more accurate versions of the water cycle when introduced into the public domain. Ultimately, new diagrams that both entertain and educate are needed to improve water literacy and foster planetary thinking in the Anthropocene. Achieving this goal depends on creative collaboration among water researchers, scholars of cognition and perception, artists and educators.

Data availability

The meta-analysis of global water pools and fluxes is included in Supplementary Table 1. The extracted data from all the diagrams is available in the Supplementary Database 1. The full set of analysed images cannot be published here because of copyright considerations, but all images are available from the corresponding author upon request.

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