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

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Main Text:

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. Though human freshwater appropriation now equals half of global river discharge, only 15% of water cycle diagrams depicted human interaction with water. Only 2% of diagrams showed climate change or water pollution—two of the central causes of the global water crisis—effectively conveying a false sense of water security. 95% of diagrams depicted a single catchment, precluding representation of teleconnections such as ocean-land interactions and continental moisture recycling. These inaccuracies correspond with specific dimensions of water mismanagement, suggesting that flaws in water diagrams reflect and reinforce misunderstanding of global hydrology by policymakers, researchers, and the public. Correcting depictions of the water cycle will not solve the global water crisis but reconceiving this symbol is an important step toward 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]. Though water cycle diagrams may not be intended as comprehensive representations of the entirety of hydrological science, they effectively play that role for many educators, policymakers, and researchers, increasing the societal stakes of systematic inaccuracies. Diagrams of the global water cycle explicitly and implicitly teach core scientific principles including 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 understanding of water and general scientific thinking[1,7,8]. Because 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 livestock, crop, and forestry use of soil moisture (green water use), water withdrawals (blue water use), and water required to assimilate pollution (gray water use; Fig. 1, Table S1)[10,11,14,15]. Second, humans have disturbed approximately three-quarters of the Earth's ice-free land surface through activities including 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, and teleconnections between water use and water availability that extend beyond the boundaries of individual catchments[17,19,28].

Because 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 analyzing their representations of it. We hypothesized that diverse worldviews and scientific approaches among disciplines and countries would influence focus, detail, and comprehensiveness of 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 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, including multiple dimensions of human water use (Fig. 1; Table S1). 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 biome, scientific field, and the number, magnitude, and ratios of water pools and fluxes, which we compared to our global water cycle synthesis. To analyze depiction of humans in the diagrams most accessed by the public, we then collected 350 diagrams from 12 countries using 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 last decade, attributable to advances in remote sensing, modeling, and regional to national accounting (Fig. 1, Table S1). Perhaps most notably, new estimates of human green, blue, and gray water use now total ~24,000 $km^3\ yr^{-1}$ (Fig. 1, Table S1)[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, Table S1).

Despite diversity across disciplines and countries, water cycle diagrams were remarkably consistent in graphical layout. Two-thirds of diagrams showed water flowing from left to right, and only four distinct formats appeared in the whole sample (Fig. S1). There were abundant commonalities in details such as placement of landscape components and elements of the water cycle, suggesting common lineage and copying (Table S3). Sixteen unique water pools and 27 unique water fluxes appeared in at least one of the 114 diagrams analyzed 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, Fig. 2). However, pool size did not influence likelihood of inclusion, with 5 of the 10 largest water pools depicted in 50% or less of diagrams (non-renewable groundwater, permafrost, saline lakes, wetlands, and soil moisture; Table 1, 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 diagrams, and the third largest flux, precipitation over the ocean, which appeared in 42% (Table 1, Fig. 2b).

We found little support for our hypotheses that diagrams would differ by audience and vary through time (Fig 2, Table S3). Patterns in the prevalence of pools and fluxes were similar for scientific and public diagrams (Figs. S2-S5) and there were even fewer differences through time, with only 1 pool and 4 fluxes showing more than 10% difference for diagrams made before and after January 1st 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) (Figs. S1-S5). Perhaps most surprisingly, 85% of the diagrams showed no interaction between humans and the water cycle. There were strong national differences in human representation, with approximately 25% of French and German diagrams integrating human activity with the water cycle, while less than 5% of Chinese, U.S., and Australian diagrams did so (Table 2). The originating discipline also influenced the depiction of human-water interactions, which appeared in approximately a third of diagrams from hydrology, natural sciences, and meteorology, but less than 15% of diagrams from the fields of land management, geography, and oceanography (Fig. S4). Representation of gray 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 diagrams and effects from climate change represented in only 1.4% of diagrams (Table 1). Green water use, which constitutes ~78% of total human water appropriation, was only shown in 3% of diagrams. Contrary to our expectation, newer diagrams were less likely to integrate humans compared to those created before 2006 (16 vs. 22%, respectively; Fig. 2).

Water diagrams implicitly and explicitly overrepresented freshwater available for human use in three ways. First, by not distinguishing saline from freshwater lakes and renewable from non-renewable groundwater, diagrams do not communicate that half of global lake volume is saline[27,33,39,40] and approximately 97% of groundwater is non-renewable on centennial timescales (insufficient recharge or not suitable for human use due to high salinity)[23,25,33,41] (Fig. 3). Even quantitative diagrams typically reported the sum volume of these pools (e.g. 190,000 km^3 for lakes and 22,600,000 km^3 for groundwater), grossly overrepresenting actual freshwater stocks. This overrepresentation is even more severe in light of recent evidence that renewable groundwater volume in many regions is less than half historic estimates, which were often based on first-order measurements or extrapolations[9,33]. Second, no diagrams indicated the proportion of pools and flows that is 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 to 5% of fresh groundwater is sustainably extractable[9,41]. This means that global accessible and sustainable blue water likely ranges from 5,000 to 9,000 $km^3\ yr^{-1}$ [10,14], coming alarmingly close to current estimates of global consumptive water use, which range from 3,800 to 5,000 $km^3\ yr^{-1}$ (Table S1)[11,21,42,43]. Third, by excluding gray water use (water pollution), diagrams did not communicate that human activity has further diminished the small fraction of accessible and sustainable freshwater by 30 to 50%[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], shaping how society relates to water[6,29,45]. Because of their high profile, 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 are likely contributing to the stubborn persistence of water cycle inaccuracies. First, a practical challenges 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, Table S1). 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 visualizations; we wish to highlight a pervasive absence and inaccuracy: the exclusion of humans and the overrepresentation of water available for human use. Another contributing factor to the rarity of depicting human influence may be aesthetic preference for natural landscapes. Proclivity for naturalness has both cultural and evolutionary roots, which could be reinforced by industrialization and urbanization[47–49], explaining the absence of humans in diagrams from some of the most developed and water-stressed countries in our sample (Table 2). However, 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, including historical context, are contributing to the absence of humans in water diagrams. Hydrology emerged as an independent scientific field of study in the U.S. 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 emphasized the natural components of the water cycle, minimizing or excluding 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], precluding 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 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 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 manipulation of vegetation[3], construction of pipelines and dams[52], and cloud seeding[53]. Without considering larger spatial scales, costly catchment interventions can exacerbate water scarcity and undermine other sustainable development goals by diverting flow from downstream and downwind communities and reducing resilience to natural and anthropogenic variability[13,48,54]. Second, lack of understanding of short- and long-term temporal change has led to overallocation of water resources and overdependence on engineered water infrastructure[55–57]. Seasonal and interannual variability in available water is a hallmark of the hydrosphere, which will only increase with climate change[12,58], but 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 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]. Though links between water flow and water chemistry have been understood for decades[62], efforts to increase water quantity routinely trigger 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]. While these inaccuracies likely 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 ensuring 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 including water security and water justice[10,28,49,51], 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 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). While 95% of the diagrams in our sample showed a single catchment, using a multi-catchment template would allow depiction of "supply-side" water dynamics, where water debits from one catchment are credits in the next via cross-continental atmospheric transport of water vapor[3,28,51]. This continental moisture recycling is the primary driver of terrestrial precipitation—150% larger than ocean-to-land atmospheric flux (Fig. 3). A diagram with multiple catchments allows intuitive understanding of water movement[67,68], communicating 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. Mismanagement of water in endorheic basins has caused some of the Earth's most serious ecological, economic, and human health catastrophes[18,27,39], though 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], enhancing coalition building and cooperative action[44,70].

Another diagrammatic need is 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], but 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 (e.g. droughts, floods, and biogeochemical pulses) not long-term averages[12–14,61]. Conveying temporal change in water diagrams could be achieved through multi-panel illustrations (insets or storyboards), labeled alternative states or ranges, and implied motion through imbalance. Additionally, new formats allow representation of temporal variability directly in animated or interactive diagrams, which have proven effective at catalyzing 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. Indeed, the same plagiarism we observed among current water cycle diagrams could facilitate rapid and broad penetration of attractive and more accurate versions of the water cycle when introduced into the public domain.

DATA AVAILABILITY: The meta-analysis of global water pools and fluxes is included in the supplementary information (Table S1). The extracted data from all diagrams is available in the attached Database S1. The full set of analyzed images cannot be published here because of copyright considerations, but all images are available from the corresponding author upon request.

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DATA SOURCES: The full meta-analysis of global water pools and fluxes is included in the supplementary information (Table S1). The extracted data from all diagrams is available in the attached Water Diagrams Database. The full set of analyzed images cannot be published here because of copyright considerations, but all images are available from the corresponding author upon request.

FINANCIAL AND NON-FINANCIAL COMPETING INTERESTS: The authors declare no competing interests.

FIGURE CAPTIONS

Table 1. Percentage of diagrams showing water pools, fluxes, and human activity.

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

Fig. 1. Estimates of major pools (a) and fluxes (b) in the global hydrological cycle based on a synthesis of ~80 recent regional and global scale studies (Table S1). 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.

Fig. 2. Percentage of water cycle diagrams representing major pools (a) and fluxes (b) in the global water cycle. Pools and fluxes are ordered by size based on Figure 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, while scientific diagrams were made for higher education textbooks and peer-reviewed publications. We compared diagrams made before and after 1 Jan 2006, corresponding with the publishing of several high-profile papers advocating increased integration of social and hydrological systems. The gray bar between points is visible for differences greater than 10 percentage points.

Fig. 3. Diagram of the global hydrological cycle in the Anthropocene. (a) Major water pools and (b) annual fluxes (uncertainty represents the range of recent estimates). We separate human use into green (soil moisture used by human crops and rangelands), blue (consumptive water use by agriculture, industry, and domestic activity), and gray (water necessary to dilute human pollutants, which are represented with pink shading). This averaged depiction of the hydrological cycle does not represent important seasonal and inter-annual variation in many pools and fluxes.

Fig. 4. Some consequences of human interference with the water cycle. While 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.

ONLINE-ONLY METHODS

Diagram collection

To identify gaps in general understanding of hydrology and implicit hypotheses held by water-related researchers, we compiled a new synthesis of the global water cycle (Table S1) and analyzed 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; 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 (External Database S1). This detailed analysis included continuous ratios of five parameters: percentage of total horizontal visual space occupied by the ocean, percentage of total precipitation and evaporation occurring on land, the ratio of 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 (e.g. buildings, fields, livestock, people), integration of humans in the water cycle (e.g. green, blue, or gray water use), and representation of climate change.

For the 114, English-language diagrams, we additionally determined 10 classifying parameters about each diagram and its producer (the person or group that created it). The diagram parameters were: date of creation; whether the water pools and fluxes were represented qualitatively or quantitatively; diagram format (catchment, hillslope, site, or schematic; Fig. S1); dimensionality of the drawing (2D or 3D); biome type represented (e.g. Arctic, Boreal, temperate, tropical, desert), and publication type (article, textbook, 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, college textbooks) or a public audience (advocacy or advertising); and scientific discipline for research and academic diagrams. Because of limited sample size for some disciplines, 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 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 dataset into diagrams created before and after January 1st 2006, corresponding with the publication of several high-profile papers that advocated 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 consistency in data extraction by analyzing every diagram at least two times (i.e. two different researchers extracted data from diagrams independently—see acknowledgments), 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 analyzed human representation in an additional set of 350 online images from 12 countries (Tables 2 and S2). 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.

Because many identical or similar diagrams appeared in the dataset, we created an automated image comparison algorithm to identify duplicate diagrams. We converted each diagram into grayscale, with each pixel associated with a value of gray from 1 to 256, and then computed the statistical distribution of gray levels for all pixels contained in each image, normalized according to image size. To find potential matches for one diagram, correlation coefficients of cumulative grayscale pixel distribution plots were calculated. The algorithm selected the top 10 potential similar items corresponding to the 10 highest correlation coefficients, and we 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, with two-thirds of diagrams showing water flowing from left to right, and only four distinct formats appearing in the whole sample (Fig. S1). 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 diagrams showed more than a single catchment, effectively precluding representation of endorheic (internally draining) basins and anthropogenic or natural interbasin water transport. There were abundant commonalities in details such as placement of landscape components and elements of the water cycle, suggesting 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 (Table S3). Most diagrams were qualitative, with only 18% including quantitative estimates of pool sizes and flux magnitudes.

There were only minor differences in the number of pools and fluxes in diagrams produced by different sectors (e.g. government, education, and advertising) or research disciplines, but detail did vary by diagram format and type, with catchment-scale diagrams and newer quantitative diagrams showing significantly more pools and fluxes based on comparisons of 95% confidence intervals of medians (Figs. S3 and S5). 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; Fig. S4, Table S3), though natural sciences (i.e. ecology, biogeochemistry, and geology) were distinct from oceanography (r = 0.65), and to a lesser extent from meteorology (r = 0.76; Table S3).

Across sectors and disciplines, only 26% of the diagrams showed ratios of ocean and land precipitation that agreed with the benchmark (i.e. 3.2 to 3.7; Fig. S2). There was no ocean precipitation at all in 58% of the diagrams, an additional 27% had approximately equal precipitation over ocean and land, and only 2% over-represented ocean precipitation (Fig. S2b). There was a split between quantitative diagrams, which usually fell within the benchmark ocean-to-land precipitation ratios, and qualitative diagrams, which never did, which explained the more accurate performance of schematic diagrams, as 70% were quantitative (Fig. S5). The same general patterns held for ocean and land evapotranspiration, with 27% of models falling in the benchmark range (i.e. 6.1 to 6.5), 65% showing equal or less evaporation from the ocean than the land, and only 8% over-representing ocean evaporation (Fig. S2). Just over a third of diagrams (36%) agreed with the benchmark estimates of the ratio of terrestrial evapotranspiration to atmospheric flux from the ocean (i.e. 1.2 to 2.1; an index of the proximate source of terrestrial precipitation [3]), 51% fell below the benchmark range, and 13% were above it (Figs. S2 and S5).

Ratios of total evapotranspiration and precipitation were more accurate but still skewed, with 63% of all diagrams falling around parity, 8% showing too little evapotranspiration, and 29% showing more evapotranspiration than precipitation (Figs. S2 and S5).

While we hypothesized that the accuracy of 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 vs. 22%, respectively; Fig. 2). The frequency of human representation did change with diagram format, with 3-dimensional catchment format diagrams showing humans interacting with water 35% of the time, but only 9% of hillslope, schematic, and site format diagrams doing so (Fig. S1). The "catchment" format diagrams are large-scale and three dimensional (upper left), "hillslope" diagrams are small scale and two dimensional (upper right), "site" diagrams integrate aspects of catchment and hillslope diagrams (lower left), and "schematic" diagrams are the most abstract representations, typically consisting of boxes and arrows (lower right).

Recommendations for improving water cycle diagrams

While true proportional representation of water cycle pools and fluxes may not be possible or desirable (e.g. showing 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, demonstrating the effectiveness of multimodal representations using both visual and numerical abstractions of the water cycle. However, assigning 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 representing poorly constrained fluxes and pools such as groundwater, human-available water, permafrost water, and human effects on evapotranspiration (Fig. 1) [9,33,54,76].

Conveying temporal change could be achieved by including multi-panel illustrations (insets or storyboards), labeled 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 catalyzing systems thinking about the water cycle [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. One of the reasons some of the more accurate diagrams have not become widespread may be that currently most diagrams integrating humans are not as artistic or professional as those showing natural landscapes. The same plagiarism or sharing that is apparent among current water cycle diagrams could facilitate rapid and broad penetration of attractive and more accurate versions of the water cycle when introduced into the public domain. Ultimately, new diagrams that entertain while they 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.

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Table 1. Percentage of diagrams showing water pools, fluxes, and human activity

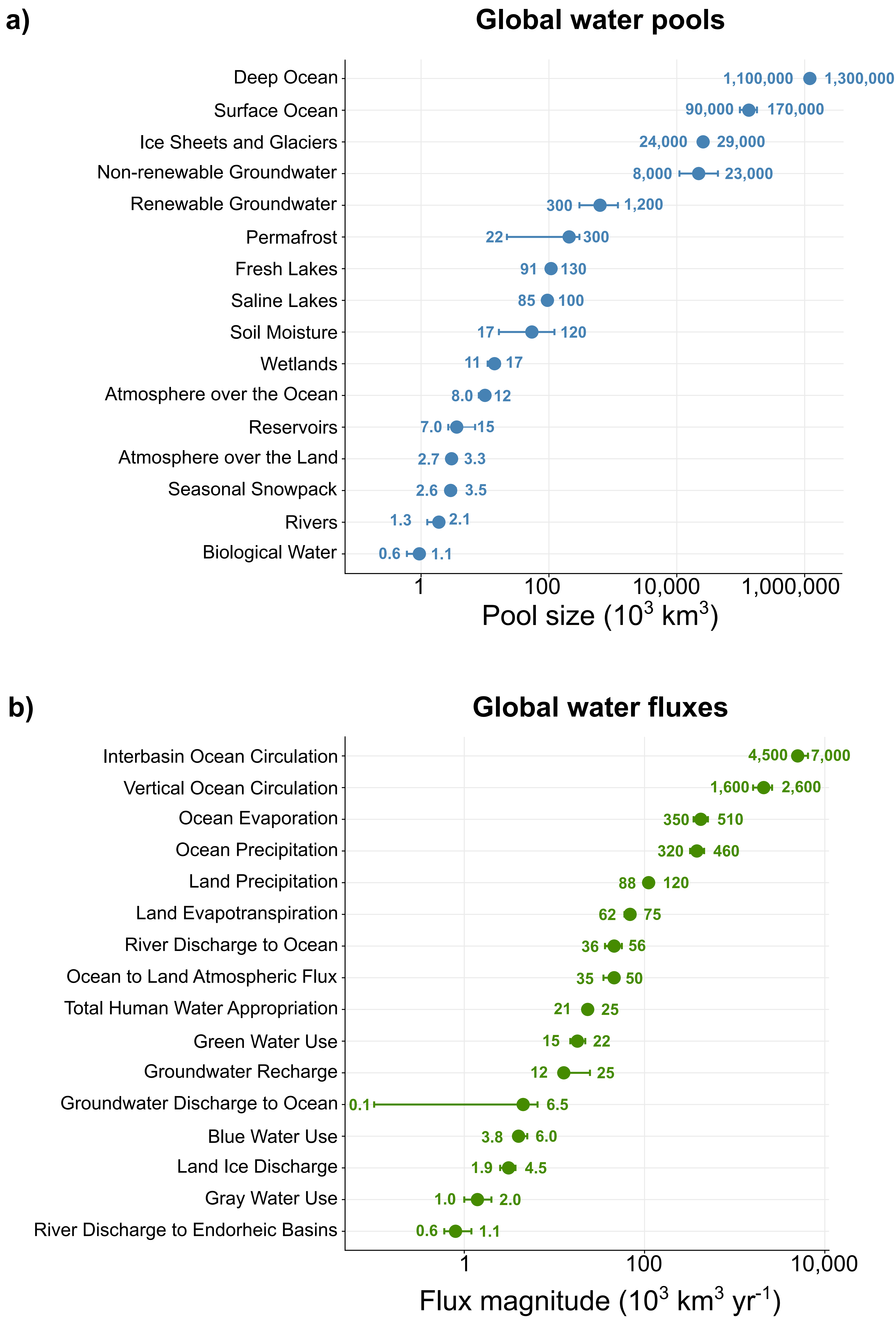
Water pools *(n=114)*	%	**Water fluxes** *(n=114)*	%
Atmosphere over the Land	94	Land Precipitation	99
Ocean	93	Condensation	88
Renewable Groundwater	81	Land Evapotranspiration	87
Rivers	77	Ocean Evaporation	85
Atmosphere over the Ocean	73	River Discharge to Ocean	75
Fresh Lakes	64	Ocean to Land Atmospheric 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
Gray water use (pollution)	2	Water capture from space	1
Climate change	1.4	Fog	1

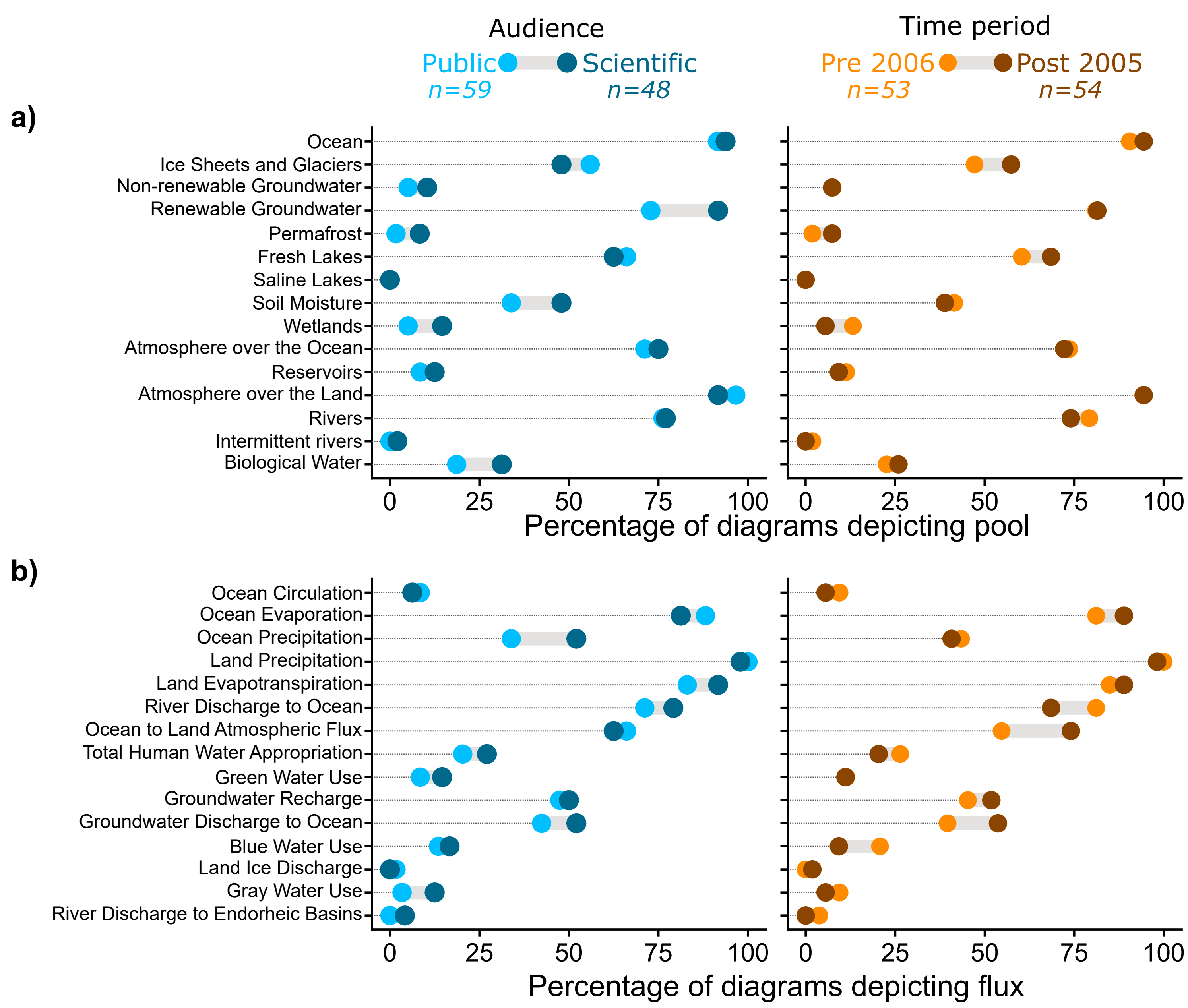
Table 2. National differences in representation of human activity in 380 water cycle diagrams.

Country*	Search language	Any sign of humans	Integrated with water cycle	Green water use	Blue water use	Gray water use (pollution)	Climate change	Overlap with main sample†
France	French	43	27	0	20	0	0	10
Germany	German	47	23	0	23	0	0	20
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
Romania	Romanian	27	20	0	7	3	3	23
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

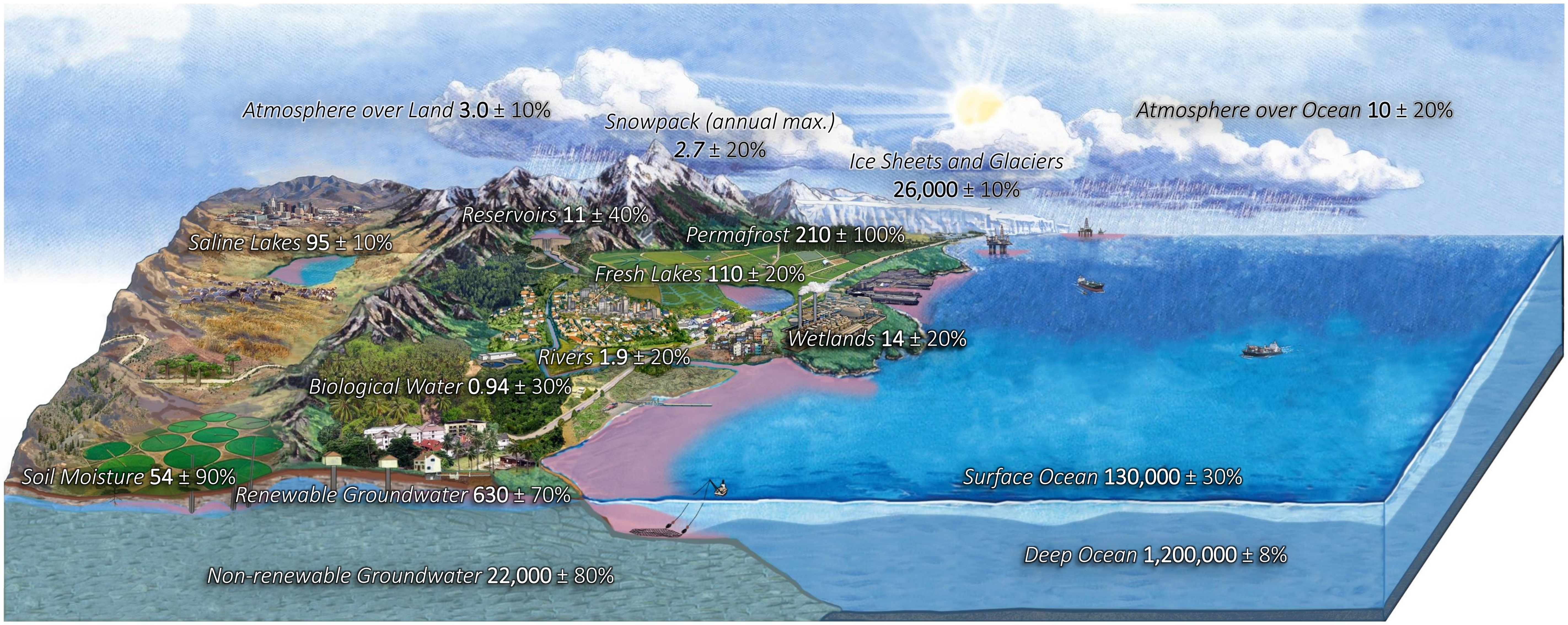
*All values are in percentage and n=30 for all countries except China where n=50. Ordered by percentage of diagrams integrating humans with water cycle. We analyzed water cycle diagrams resulting from online image searches of the term “water cycle” or its translation for 12 countries. Searches were performed on Baidu.com for China and Google.com for all other countries.

†Percentage of diagrams from the country-specific image search also occurring in the sample of 114 water cycle diagrams analyzed for the whole suite of characteristics.

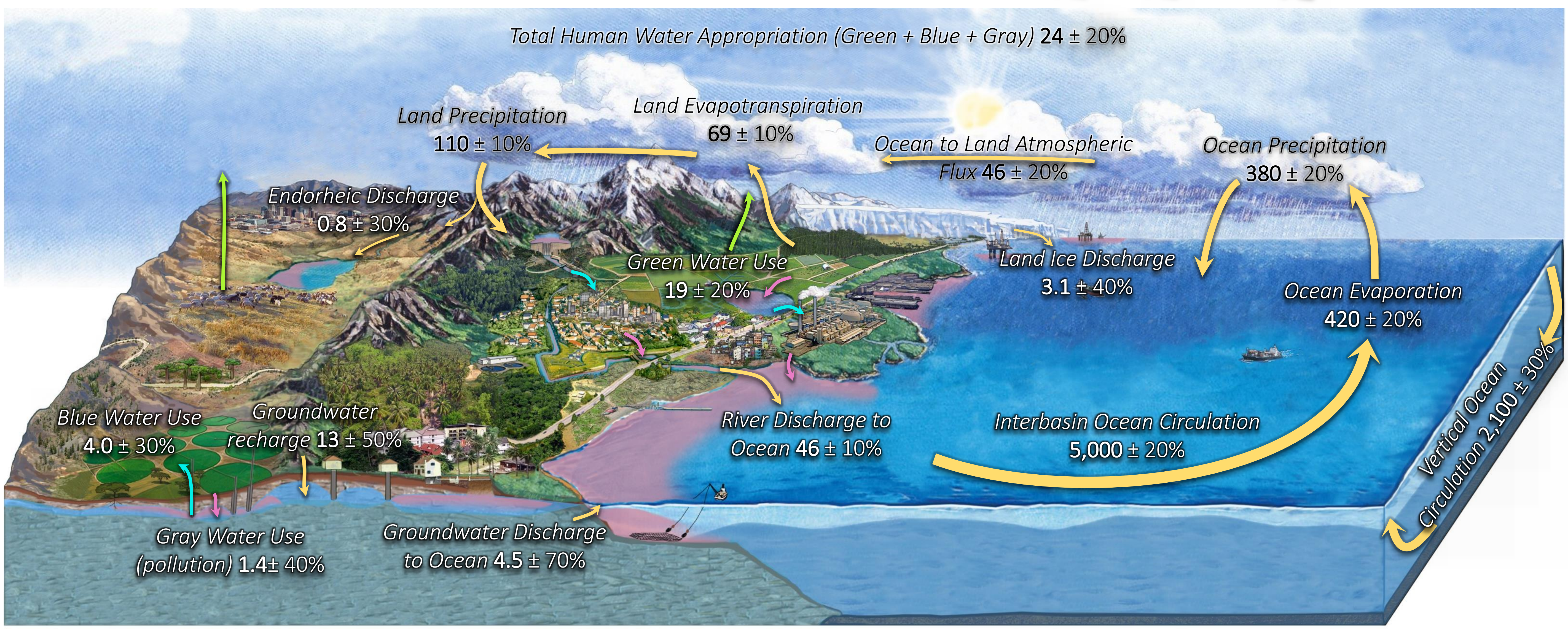

a)
Global water pools
Deep Ocean 1,100,000 1,300,000
Surface Ocean 90,000 170,000
Ice Sheets and Glaciers 24,000 29,000
Non-renewable Groundwater 8,000 23,000
Renewable Groundwater 300 1,200
Permafrost 22 300
Fresh Lakes 91 130
Saline Lakes 85 100
Soil Moisture 17 120
Wetlands 11 17
Atmosphere over the Ocean 8.0 12
Reservoirs 7.0 15
Atmosphere over the Land 2.7 3.3
Seasonal Snowpack 2.6 3.5
Rivers 1.3 2.1
Biological Water 0.6 1.1
1
100
10,000
1,000,000
Pool size (10^3 km^3)
b)
Global water fluxes
Interbasin Ocean Circulation 4,500 7,000
Vertical Ocean Circulation 1,600 2,600
Ocean Evaporation 350 510
Ocean Precipitation 320 460
Land Precipitation 88 120
Land Evapotranspiration 62 75
River Discharge to Ocean 36 56
Ocean to Land Atmospheric Flux 35 50
Total Human Water Appropriation 21 25
Green Water Use 15 22
Groundwater Recharge 12 25
Groundwater Discharge to Ocean 0.1 6.5
Blue Water Use 3.8 6.0
Land Ice Discharge 1.9 4.5
Gray Water Use 1.0 2.0
River Discharge to Endorheic Basins 0.6 1.1
1
100
10,000
Flux magnitude (10^3 km^3 yr^{-1})


Audience
Public
Scientific
n=59
n=48
Time period
Pre 2006
Post 2005
n=53
n=54
a)
Ocean
Ice Sheets and Glaciers
Non-renewable Groundwater
Renewable Groundwater
Permafrost
Fresh Lakes
Saline Lakes
Soil Moisture
Wetlands
Atmosphere over the Ocean
Reservoirs
Atmosphere over the Land
Rivers
Intermittent rivers
Biological Water
0 25 50 75 100
Percentage of diagrams depicting pool
b)
Ocean Circulation
Ocean Evaporation
Ocean Precipitation
Land Precipitation
Land Evapotranspiration
River Discharge to Ocean
Ocean to Land Atmospheric Flux
Total Human Water Appropriation
Green Water Use
Groundwater Recharge
Groundwater Discharge to Ocean
Blue Water Use
Land Ice Discharge
Gray Water Use
River Discharge to Endorheic Basins
Percentage of diagrams depicting flux

a) Major pools in the global hydrological cycle expressed in 10^3 km^3. For panels a and b, uncertainty is expressed in ± % based on the range of recent estimates.



b) Major fluxes in the global hydrological cycle in 10^3 km^3 yr^{-1}. Human water appropriation is separated into Green, Blue, and Gray, water use.




Land conversion (agriculture, deforestation, wetland loss) alters continental moisture recycling to downwind catchments
Extreme weather (drought and flood) and overall intensification of hydrological cycle
Flood damage from modified flow regimes (e.g. dikes, dams, and drains) and loss of floodplains and wetlands
Discharge from ice sheets, glaciers, and permafrost
Volatility of terminal lakes and rivers from agricultural and urban water diversions
Altered ocean currents and associated teleconnections with climate
Long-distance trade of actual and virtual water
Increased temperature and intermittency of river flow
Known and novel pollutants from agriculture, industry, and domestic activity
Depletion and contamination of renewable groundwater at the same time that reliance on subsurface water increases
Water scarcity from socioeconomic inequality, land degradation, or poor water governance
Expansion of dead zones from nutrient loading and warmer water
Sea level rise and saltwater intrusion
Primary dimension of human interference:
Land use
Climate change
Water use