

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

Abbott, Benjamin W.; Bishop, Kevin; Zarnetske, Jay P.; Minaudo, Camille; Chapin, F. S.; Krause, Stefan; Hannah, David M.; Conner, Lafe; Ellison, David; Godsey, Sarah E.; Plont, Stephen; Marçais, Jean; Kolbe, Tamara; Huebner, Amanda; Frei, Rebecca J.; Hampton, Tyler; Gu, Sen; Buhman, Madeline; Sayedi, Sayedeh Sara; Ursache, Ovidiu

DOI:

[10.1038/s41561-019-0374-y](https://doi.org/10.1038/s41561-019-0374-y)

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Document Version

Peer reviewed version

Citation for published version (Harvard):

Abbott, BW, Bishop, K, Zarnetske, JP, Minaudo, C, Chapin, FS, Krause, S, Hannah, DM, Conner, L, Ellison, D, Godsey, SE, Plont, S, Marçais, J, Kolbe, T, Huebner, A, Frei, RJ, Hampton, T, Gu, S, Buhman, M, Sayedi, SS, Ursache, O, Chapin, M, Henderson, KD & Pinay, G 2019, 'Human domination of the global water cycle absent from depictions and perceptions', *Nature Geoscience*, vol. 12, no. 7, pp. 533-540.
<https://doi.org/10.1038/s41561-019-0374-y>

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Checked for eligibility: 21/10/2019

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1 **Title:**

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

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35 **Main Text:**

36 **Human water use, climate change, and land conversion have created a water crisis for**
37 **billions of individuals and many ecosystems worldwide. Global water stocks and fluxes are**
38 **estimated empirically and with computer models, but this information is conveyed to**
39 **policymakers and researchers through water cycle diagrams. Here, we compiled a synthesis**
40 **of the global water cycle, which we compared with 464 water cycle diagrams from around**
41 **the world. Though human freshwater appropriation now equals half of global river**
42 **discharge, only 15% of water cycle diagrams depicted human interaction with water. Only**
43 **2% of diagrams showed climate change or water pollution—two of the central causes of the**
44 **global water crisis—effectively conveying a false sense of water security. 95% of diagrams**
45 **depicted a single catchment, precluding representation of teleconnections such as ocean-**
46 **land interactions and continental moisture recycling. These inaccuracies correspond with**
47 **specific dimensions of water mismanagement, suggesting that flaws in water diagrams**
48 **reflect and reinforce misunderstanding of global hydrology by policymakers, researchers,**
49 **and the public. Correcting depictions of the water cycle will not solve the global water crisis**
50 **but reconceiving this symbol is an important step toward equitable water governance,**
51 **sustainable development, and planetary thinking in the Anthropocene.**

52 The water cycle is one of the first great cycles with which many people engage during
53 their basic education^{1,2}. In the absence of direct experience with large-scale hydrological
54 processes, these diagrams form the basis of our valuation and management of the global water
55 cycle³⁻⁶. Though water cycle diagrams may not be intended as comprehensive representations of
56 the entirety of hydrological science, they effectively play that role for many educators,
57 policymakers, and researchers, increasing the societal stakes of systematic inaccuracies. Diagrams
58 of the global water cycle explicitly and implicitly teach core scientific principles including
59 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 destruction¹⁶. 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 $\sim 24,000 \text{ km}^3 \text{ yr}^{-1}$ (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 storage³⁶, non-renewable groundwater³³, and groundwater recharge³⁷ 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

134 between humans and the water cycle. There were strong national differences in human
135 representation, with approximately 25% of French and German diagrams integrating human
136 activity with the water cycle, while less than 5% of Chinese, U.S., and Australian diagrams did so
137 (Table 2). The originating discipline also influenced the depiction of human-water interactions,
138 which appeared in approximately a third of diagrams from hydrology, natural sciences, and
139 meteorology, but less than 15% of diagrams from the fields of land management, geography, and
140 oceanography (Fig. S4). Representation of gray water use and climate-mediated interference with
141 the water cycle was extremely rare across disciplines and countries, with water pollution depicted
142 in only 2% of diagrams and effects from climate change represented in only 1.4% of diagrams
143 (Table 1). Green water use, which constitutes ~78% of total human water appropriation, was only
144 shown in 3% of diagrams. Contrary to our expectation, newer diagrams were less likely to
145 integrate humans compared to those created before 2006 (16 vs. 22%, respectively; Fig. 2).

146 Water diagrams implicitly and explicitly overrepresented freshwater available for human
147 use in three ways. First, by not distinguishing saline from freshwater lakes and renewable from
148 non-renewable groundwater, diagrams do not communicate that half of global lake volume is
149 saline^{27,33,39,40} and approximately 97% of groundwater is non-renewable on centennial timescales
150 (insufficient recharge or not suitable for human use due to high salinity)^{23,25,33,41} (Fig. 3). Even
151 quantitative diagrams typically reported the sum volume of these pools (e.g. 190,000 km³ for
152 lakes and 22,600,000 km³ for groundwater), grossly overrepresenting actual freshwater stocks.
153 This overrepresentation is even more severe in light of recent evidence that renewable
154 groundwater volume in many regions is less than half historic estimates, which were often based
155 on first-order measurements or extrapolations^{9,33}. Second, no diagrams indicated the proportion of
156 pools and flows that is accessible for human use. Less than 10% of annual terrestrial precipitation
157 and 25% of annual river flow are sustainably available for human consumptive use³⁰, and only 1
158 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 km³ yr⁻¹ ^{10,14}, coming alarmingly close to current estimates of global consumptive water use, which range from 3,800 to 5,000 km³ 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

184 in diagrams from some of the most developed and water-stressed countries in our sample (Table
185 2). However, image searches for “global carbon cycle” and “global nitrogen cycle” reveal that
186 97% and 87% depict human activity, respectively (based on the first 30 results). This suggests
187 that other dynamics, including historical context, are contributing to the absence of humans in
188 water diagrams. Hydrology emerged as an independent scientific field of study in the U.S. in the
189 1930s, coincident with the popularization of modern water cycle diagrams^{6,49}. Partly in an effort
190 to establish hydrology as a natural science distinct from civil engineering and agronomy, these
191 conceptual models emphasized the natural components of the water cycle, minimizing or
192 excluding human activity^{6,31}. Perhaps most fundamentally, large-scale anthropogenic effects on
193 the water cycle were less extensive and less understood a century ago^{18,34,50}, precluding
194 representation of land use affecting downwind catchments and other teleconnections^{28,51}.
195 Together, these practical, aesthetic, and historical factors may have counteracted efforts to
196 integrate humans into depictions of the water cycle^{4,49}.

197 On the second question of whether water cycle inaccuracies contribute to mismanagement
198 of water resources, four of the diagrammatic flaws we found here correspond directly with current
199 failings in water management (Fig. 4). First, disregard of hydrological teleconnections between
200 oceans and continents and among catchments has led to attempts to solve water scarcity with
201 single-catchment interventions. Such “demand-side” approaches to water management include
202 manipulation of vegetation³, construction of pipelines and dams⁵², and cloud seeding⁵³. Without
203 considering larger spatial scales, costly catchment interventions can exacerbate water scarcity and
204 undermine other sustainable development goals by diverting flow from downstream and
205 downwind communities and reducing resilience to natural and anthropogenic variability^{13,48,54}.
206 Second, lack of understanding of short- and long-term temporal change has led to overallocation
207 of water resources and overdependence on engineered water infrastructure^{55–57}. Seasonal and
208 interannual variability in available water is a hallmark of the hydrosphere, which will only

209 increase with climate change^{12,58}, but 99% of the diagrams in our sample and many water
210 regulatory frameworks worldwide assume that water resources are stable on seasonal to
211 interannual timescales^{5,10}. Disregard of temporal variability means that groundwater is extracted
212 faster than it is recharged at a global scale^{9,23,25}, terminal (endorheic) lakes and wetlands are in
213 decline on every continent except Antarctica^{27,39}, and semi-arid regions are experiencing
214 desertification^{21,22}. Third, water quality and water quantity are often treated as separate issues due
215 to technical, legal, and disciplinary differences^{52,59–61}. Though links between water flow and water
216 chemistry have been understood for decades⁶², efforts to increase water quantity routinely trigger
217 eutrophication of fresh and saltwater ecosystems^{63,64}, salinization⁶⁵, and ultimately reductions in
218 useable water^{14,27}. Fourth, much of current water management focuses on securing water supply
219 rather than managing water demand^{28,32}. This approach presumes that water scarcity is determined
220 exclusively by climate and that human water use is effectively unchangeable^{3,51,66}. While these
221 inaccuracies likely reflect as much as they reinforce bad water policy, depictions of abundant and
222 pristine freshwater resources, so common in water cycle diagrams, belie the need for land
223 conservation and water efficiency, which are critical to ensuring societal and ecological water
224 flows in a changing world^{10,28,45}.

225 **A water cycle for the Anthropocene**

226 The omission of humans and associated changes from water cycle diagrams is deeply
227 problematic because it implies that one of our most essential and threatened resources is not
228 influenced by our actions. The exclusion of humans obscures some of the most urgent
229 socioecological crises including water security and water justice^{10,28,49,51}, loss of aquatic
230 biodiversity^{13,26}, climate change^{20,24}, and freshwater and coastal eutrophication^{14,18}. Given the
231 immense scale of human suffering and ecological destruction associated with the global water
232 crisis, we need to bring to bear all our scientific and cultural faculties to increase understanding
233 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

259 averages^{12–14,61}. Conveying temporal change in water diagrams could be achieved through multi-
260 panel illustrations (insets or storyboards), labeled alternative states or ranges, and implied motion
261 through imbalance. Additionally, new formats allow representation of temporal variability
262 directly in animated or interactive diagrams, which have proven effective at catalyzing deeper
263 thinking about complex systems⁷¹.

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

269
270 **DATA AVAILABILITY:** The meta-analysis of global water pools and fluxes is included in the
271 supplementary information (Table S1). The extracted data from all diagrams is available in the
272 attached Database S1. The full set of analyzed images cannot be published here because of
273 copyright considerations, but all images are available from the corresponding author upon
274 request.

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412

413 **ACKNOWLEDGEMENTS:** Financial support for this study was provided by the Department of
414 Plant and Wildlife Sciences and College of Life Sciences at Brigham Young University and by
415 the European Union's Seventh Framework Program for research, technological development and
416 demonstration under grant agreement no. 607150 (FP7-PEOPLE-2013-ITN-INTERFACES -
417 Ecohydrological interfaces as critical hotspots for transformations of ecosystem exchange fluxes
418 and biogeochemical cycling). We thank T. Burt, S. Abbott, J. Howe, C. Ash, and six anonymous
419 reviewers for input on the manuscript and we thank S. Chowdhury for assistance with diagram
420 analysis.

421 **AUTHOR CONTRIBUTIONS:** The concept for this paper emerged during discussion among
422 BWA, KB, GP, TK, DH, SK, and JPZ in Rennes, France in 2015. SP, SEG, TK, JM, OU, MC,
423 RJF, BWA, and MB downloaded and analyzed diagrams. Diane Conner, BWA, LC, JPZ, KDH,
424 OU, MC, RJF, and TH created Figures 3 and 4 with input from all co-authors. BWA and CM
425 managed data and performed statistical analyses. BWA wrote the manuscript with input from all
426 co-authors.

427
428 **DATA SOURCES:** The full meta-analysis of global water pools and fluxes is included in the
429 supplementary information (Table S1). The extracted data from all diagrams is available in the
430 attached Water Diagrams Database. The full set of analyzed images cannot be published here
431 because of copyright considerations, but all images are available from the corresponding author
432 upon request.

433
434 **FINANCIAL AND NON-FINANCIAL COMPETING INTERESTS:** The authors declare no
435 competing interests.

436

437

438

439 **FIGURE CAPTIONS**

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

441

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

443

444 **Fig. 1.** Estimates of major pools (a) and fluxes (b) in the global hydrological cycle based on a
445 synthesis of ~80 recent regional and global scale studies (Table S1). The central point represents
446 the most recent or comprehensive individual estimate, and error bars represent the range of
447 reported values and their uncertainties. Note the log scales on the x-axes.

448

449 **Fig. 2.** Percentage of water cycle diagrams representing major pools (a) and fluxes (b) in the
450 global water cycle. Pools and fluxes are ordered by size based on Figure 1, starting with the
451 largest pool (ocean) and flux (ocean circulation). We categorized diagrams by intended audience
452 and time period. Public diagrams include those made for advertising, advocacy, government
453 outreach, and primary or secondary education, while scientific diagrams were made for higher
454 education textbooks and peer-reviewed publications. We compared diagrams made before and
455 after 1 Jan 2006, corresponding with the publishing of several high-profile papers advocating
456 increased integration of social and hydrological systems. The gray bar between points is visible
457 for differences greater than 10 percentage points.

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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.

472 **ONLINE-ONLY METHODS**

473 **Diagram collection**

474 To identify gaps in general understanding of hydrology and implicit hypotheses held by
475 water-related researchers, we compiled a new synthesis of the global water cycle (Table S1) and
476 analyzed 464 diagrams of the water cycle. Initially, we collected 114 diagrams from textbooks,
477 scientific articles, teaching materials, advertisements, and agency reports, which we identified by
478 querying Web of Science, Google Scholar, and Google Books. To avoid bias in this selection, no
479 representations of the water cycle were excluded. To assess diagrams most accessed by the
480 public, we then collected the top 30 diagrams that appeared in an online image search for “water
481 cycle” in 12 countries translated into the local language, using the Baidu search engine for China,
482 and Google for all other countries (Table 2; details below).

483 **Visual analysis**

484 For the initial sample of 114 diagrams published in English, we extracted 52 parameters
485 based on the visual representation of the water cycle (External Database S1). This detailed
486 analysis included continuous ratios of five parameters: percentage of total horizontal visual space
487 occupied by the ocean, percentage of total precipitation and evaporation occurring on land, the
488 ratio of overall evapotranspiration to precipitation, and the ratio of terrestrial evapotranspiration to
489 ocean to land atmospheric water transport. We also quantified the presence or absence of 17 water
490 pools and 27 water fluxes (Table 1), signs of human activity (e.g. buildings, fields, livestock,
491 people), integration of humans in the water cycle (e.g. green, blue, or gray water use), and
492 representation of climate change.

493 For the 114, English-language diagrams, we additionally determined 10 classifying
494 parameters about each diagram and its producer (the person or group that created it). The diagram
495 parameters were: date of creation; whether the water pools and fluxes were represented

496 qualitatively or quantitatively; diagram format (catchment, hillslope, site, or schematic; Fig. S1);
497 dimensionality of the drawing (2D or 3D); biome type represented (e.g. Arctic, Boreal, temperate,
498 tropical, desert), and publication type (article, textbook, online). The producer parameters were:
499 producer type, which indicates whether the diagram was created by researchers for peer-reviewed
500 articles or reports (research), by a governmental agency (government), for use in higher education
501 (academic), for use in primary or secondary education (education), for use in advertising, or for
502 advocacy purposes; whether the diagram was intended for a scientific audience (articles, reports,
503 college textbooks) or a public audience (advocacy or advertising); and scientific discipline for
504 research and academic diagrams. Because of limited sample size for some disciplines, we grouped
505 agronomy, forestry, and soil science into a land management category, and ecosystem ecology,
506 biogeochemistry, aquatic ecology, and geology into a natural sciences category. For all
507 disciplinary classifications, we considered first the publication outlet, followed by the primary
508 research discipline of the lead author, and finally her or his departmental affiliation. To test for
509 changes through time, we split the dataset into diagrams created before and after January 1st 2006,
510 corresponding with the publication of several high-profile papers that advocated better integration
511 of humans into conceptualizations of the water cycle^{6,30,72,73}. This separation also provided
512 relatively balanced sample sizes between the two periods.

513 For both the initial sample of English-language diagrams and for the international
514 comparison described below, we ensured consistency in data extraction by analyzing every
515 diagram at least two times (i.e. two different researchers extracted data from diagrams
516 independently—see acknowledgments), and the lead author performed a final verification of
517 every diagram and associated data.

518 **International comparison**

519 To test if the patterns observed in our initial sample of technical, English-language
520 diagrams held for non-technical diagrams, we analyzed human representation in an additional set

521 of 350 online images from 12 countries (Tables 2 and S2). We systematically collected the most-
522 accessed 30 diagrams for 12 countries by performing an online image search for “water cycle”
523 translated into the local language, using the Baidu search engine for China, and Google for all
524 other countries. As for the set of initial diagrams, we did not exclude any images of the water
525 cycle, to avoid potential sampling bias.

526 Because many identical or similar diagrams appeared in the dataset, we created an
527 automated image comparison algorithm to identify duplicate diagrams. We converted each
528 diagram into grayscale, with each pixel associated with a value of gray from 1 to 256, and then
529 computed the statistical distribution of gray levels for all pixels contained in each image,
530 normalized according to image size. To find potential matches for one diagram, correlation
531 coefficients of cumulative grayscale pixel distribution plots were calculated. The algorithm
532 selected the top 10 potential similar items corresponding to the 10 highest correlation coefficients,
533 and we identified true duplication manually.

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

536 **Detailed analysis of water cycle diagrams**

537 Water cycle diagrams were remarkably consistent in graphical layout, with two-thirds of
538 diagrams showing water flowing from left to right, and only four distinct formats appearing in the
539 whole sample (Fig. S1). Of the diagrams with an identifiable biome, 92% depicted temperate
540 ecosystems, 5% showed Boreal ecosystems, 2% showed arid ecosystems, and 1% depicted
541 multiple biomes. Only 5% of diagrams showed more than a single catchment, effectively
542 precluding representation of endorheic (internally draining) basins and anthropogenic or natural
543 interbasin water transport. There were abundant commonalities in details such as placement of
544 landscape components and elements of the water cycle, suggesting widespread copying. This was
545 particularly true for diagrams found through online image searches, where many images were

546 slight modifications of material from textbooks, government outreach, or research articles (Table
547 S3). Most diagrams were qualitative, with only 18% including quantitative estimates of pool sizes
548 and flux magnitudes.

549 There were only minor differences in the number of pools and fluxes in diagrams
550 produced by different sectors (e.g. government, education, and advertising) or research
551 disciplines, but detail did vary by diagram format and type, with catchment-scale diagrams and
552 newer quantitative diagrams showing significantly more pools and fluxes based on comparisons
553 of 95% confidence intervals of medians (Figs. S3 and S5). Diagrams from different disciplines
554 generally showed the same patterns in percentage representation of individual pools and fluxes
555 (mean of pairwise Pearson's $r = 0.88$; Fig. S4, Table S3), though natural sciences (i.e. ecology,
556 biogeochemistry, and geology) were distinct from oceanography ($r = 0.65$), and to a lesser extent
557 from meteorology ($r = 0.76$; Table S3).

558 Across sectors and disciplines, only 26% of the diagrams showed ratios of ocean and land
559 precipitation that agreed with the benchmark (i.e. 3.2 to 3.7; Fig. S2). There was no ocean
560 precipitation at all in 58% of the diagrams, an additional 27% had approximately equal
561 precipitation over ocean and land, and only 2% over-represented ocean precipitation (Fig. S2b).
562 There was a split between quantitative diagrams, which usually fell within the benchmark ocean-
563 to-land precipitation ratios, and qualitative diagrams, which never did, which explained the more
564 accurate performance of schematic diagrams, as 70% were quantitative (Fig. S5). The same
565 general patterns held for ocean and land evapotranspiration, with 27% of models falling in the
566 benchmark range (i.e. 6.1 to 6.5), 65% showing equal or less evaporation from the ocean than the
567 land, and only 8% over-representing ocean evaporation (Fig. S2). Just over a third of diagrams
568 (36%) agreed with the benchmark estimates of the ratio of terrestrial evapotranspiration to
569 atmospheric flux from the ocean (i.e. 1.2 to 2.1; an index of the proximate source of terrestrial
570 precipitation³), 51% fell below the benchmark range, and 13% were above it (Figs. S2 and S5).

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

574 While we hypothesized that the accuracy of diagrams would improve through time due to
575 advances in global hydrology and concerted efforts to better integrate humans into depictions of
576 the water cycle ^{6,30,75}, newer diagrams were actually less likely to integrate humans compared to
577 those created before 2006 (16 vs. 22%, respectively; Fig. 2). The frequency of human
578 representation did change with diagram format, with 3-dimensional catchment format diagrams
579 showing humans interacting with water 35% of the time, but only 9% of hillslope, schematic, and
580 site format diagrams doing so (Fig. S1). The “catchment” format diagrams are large-scale and
581 three dimensional (upper left), “hillslope” diagrams are small scale and two dimensional (upper
582 right), “site” diagrams integrate aspects of catchment and hillslope diagrams (lower left), and
583 “schematic” diagrams are the most abstract representations, typically consisting of boxes and
584 arrows (lower right).

585 **Recommendations for improving water cycle diagrams**

586 While true proportional representation of water cycle pools and fluxes may not be possible
587 or desirable (e.g. showing the ocean one million times larger than rivers), creators of water
588 diagrams should be aware of the relative magnitudes of fluxes and pools, which allows deliberate
589 divergences in any specific presentation ². In our sample, quantitative diagrams were more
590 accurate than non-quantitative diagrams in all the dimensions we measured, demonstrating the
591 effectiveness of multimodal representations using both visual and numerical abstractions of the
592 water cycle. However, assigning a single number to a flux or pool may undermine the depiction
593 of temporal change and imply a lack of uncertainty ⁵. Visual and numerical estimates should be
594 accompanied by uncertainty ranges ⁵⁹, particularly when representing poorly constrained fluxes

595 and pools such as groundwater, human-available water, permafrost water, and human effects on
596 evapotranspiration (Fig. 1) ^{9,33,54,76}.

597 Conveying temporal change could be achieved by including multi-panel illustrations
598 (insets or storyboards), labeled alternative states or ranges, and implied motion through imbalance
599 ^{5,77}. It is also possible to depict temporal change explicitly with animated and interactive models.
600 Gamification, virtual reality, and augmented reality approaches can be effective at catalyzing
601 systems thinking about the water cycle ⁷¹.

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

612

613 **References only in Methods**

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Table 1. Percentage of diagrams showing water pools, fluxes, and human activity 2

Water pools (<i>n</i>=114)	%	Water fluxes (<i>n</i>=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 (<i>n</i>=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

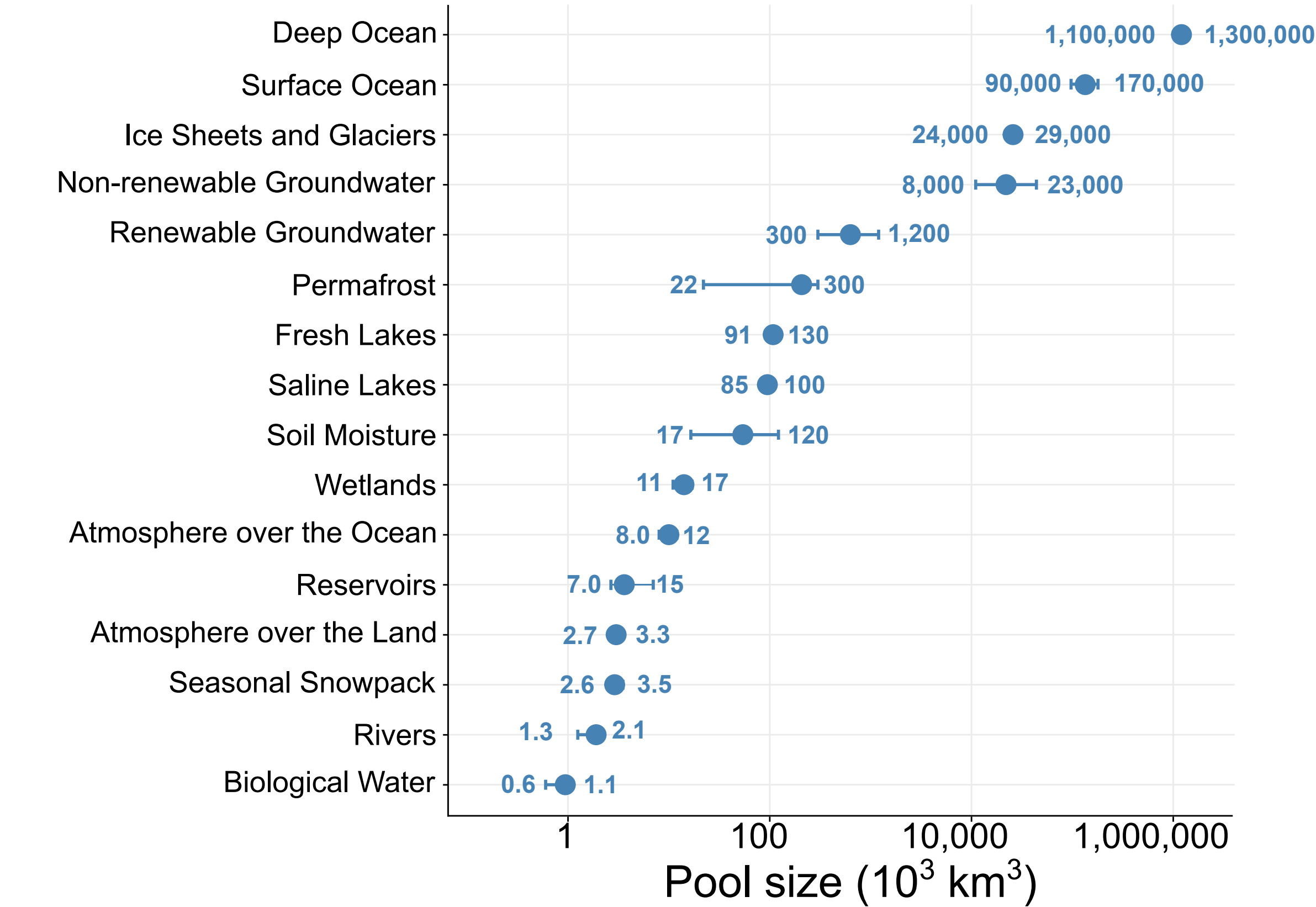
1 **Table 2.** National differences in representation of human activity in 380 water cycle diagrams.

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

2 *All values are in percentage and n=30 for all countries except China where n=50. Ordered by percentage of diagrams integrating humans with
3 water cycle. We analyzed water cycle diagrams resulting from online image searches of the term “water cycle” or its translation for 12 countries.
4 Searches were performed on Baidu.com for China and Google.com for all other countries.
5 [†]Percentage of diagrams from the country-specific image search also occurring in the sample of 114 water cycle diagrams analyzed for the whole
6 suite of characteristics.

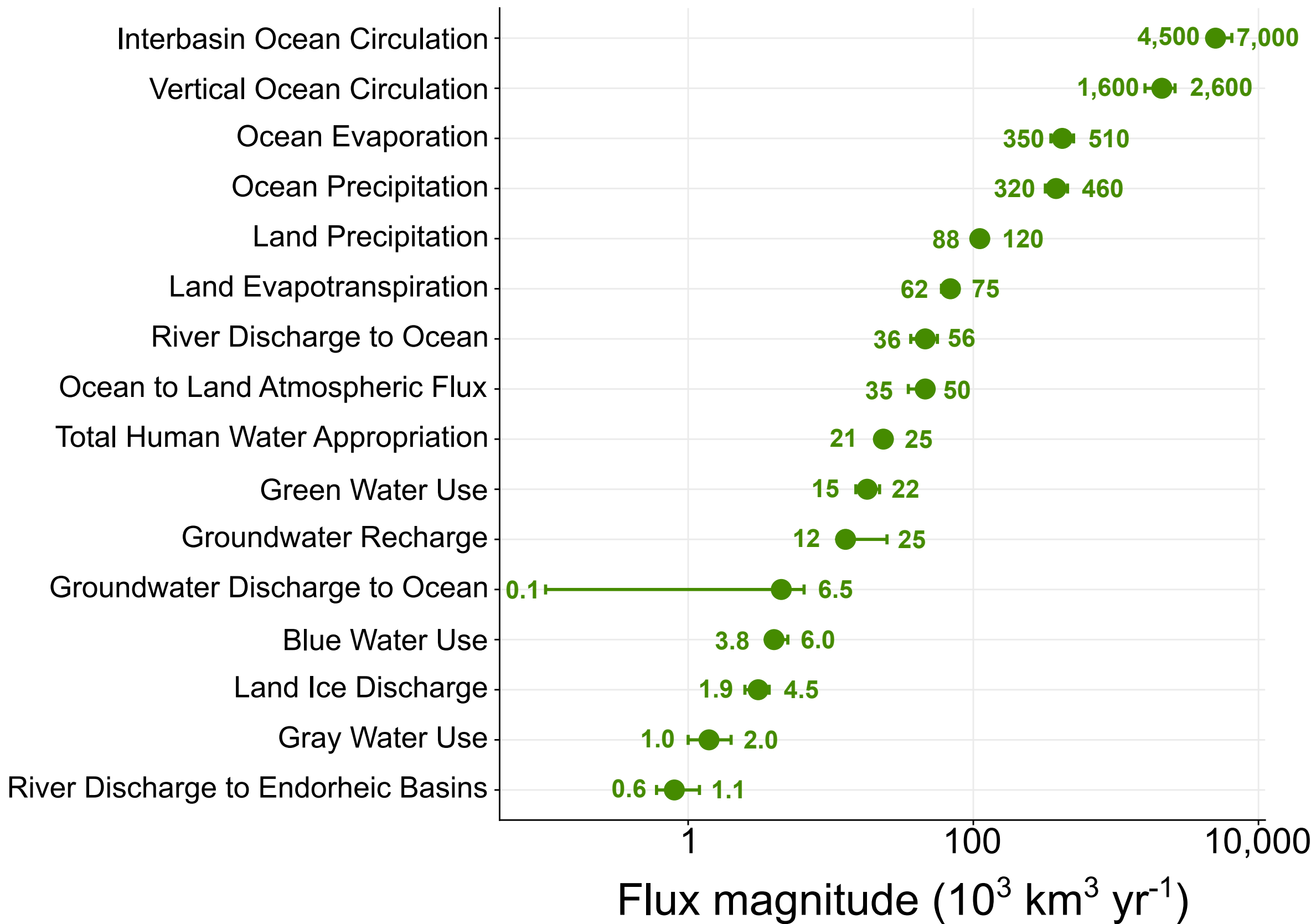
a)

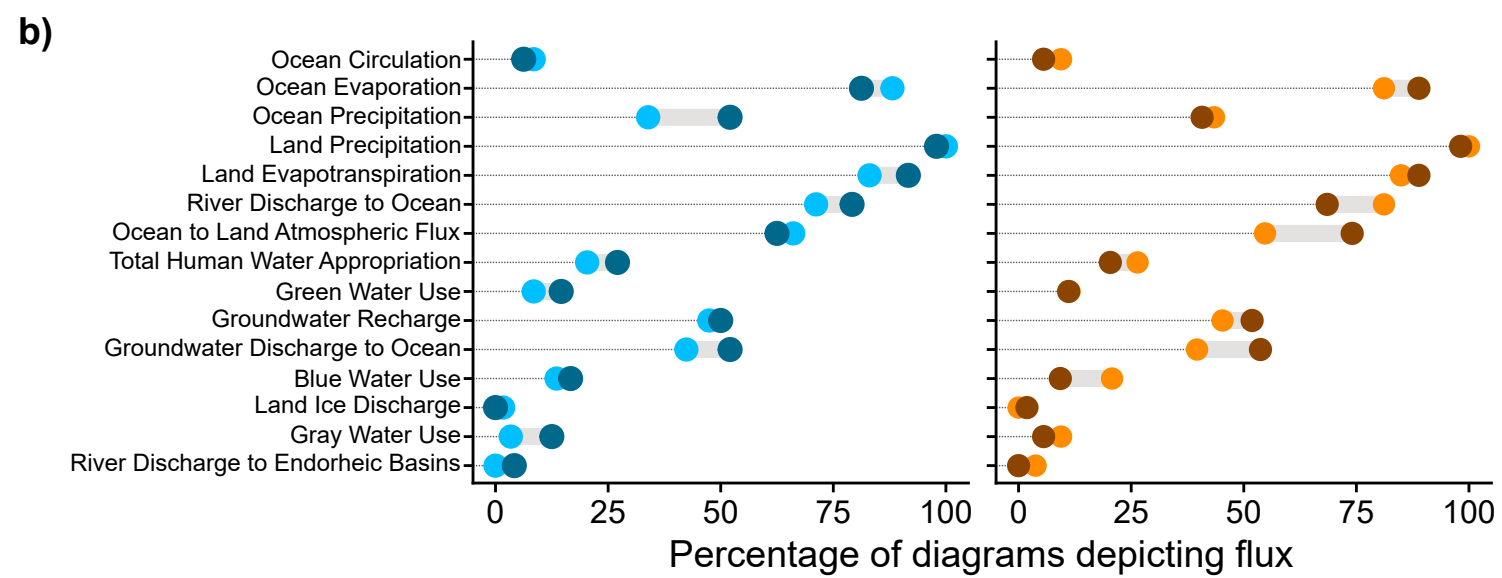
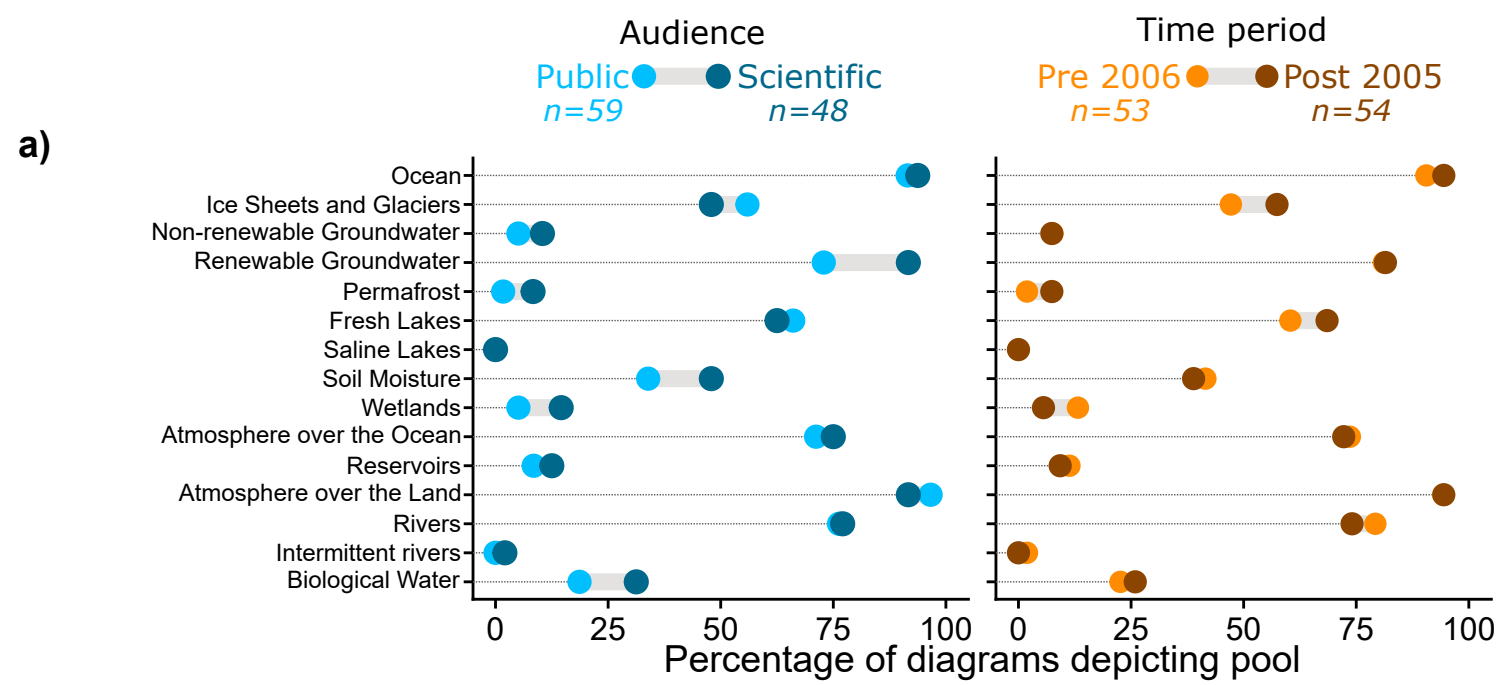
Global water pools



b)




Global water fluxes

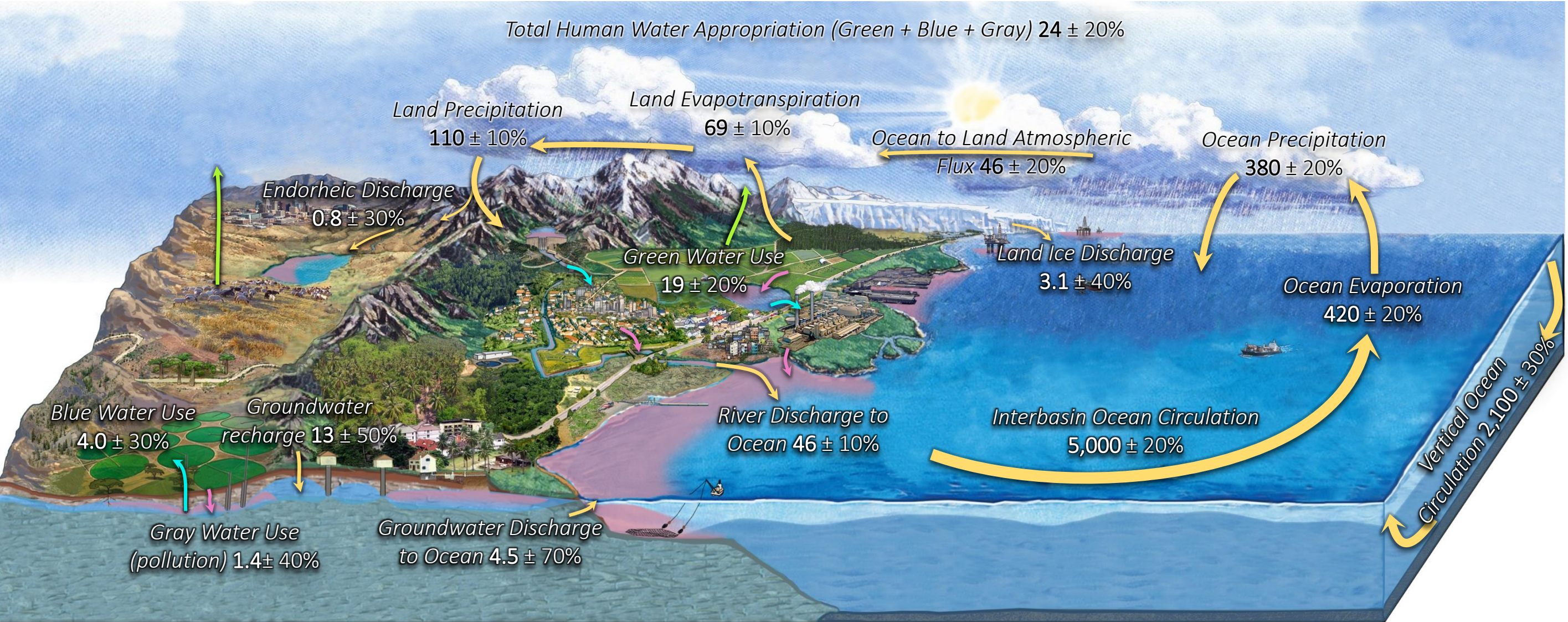


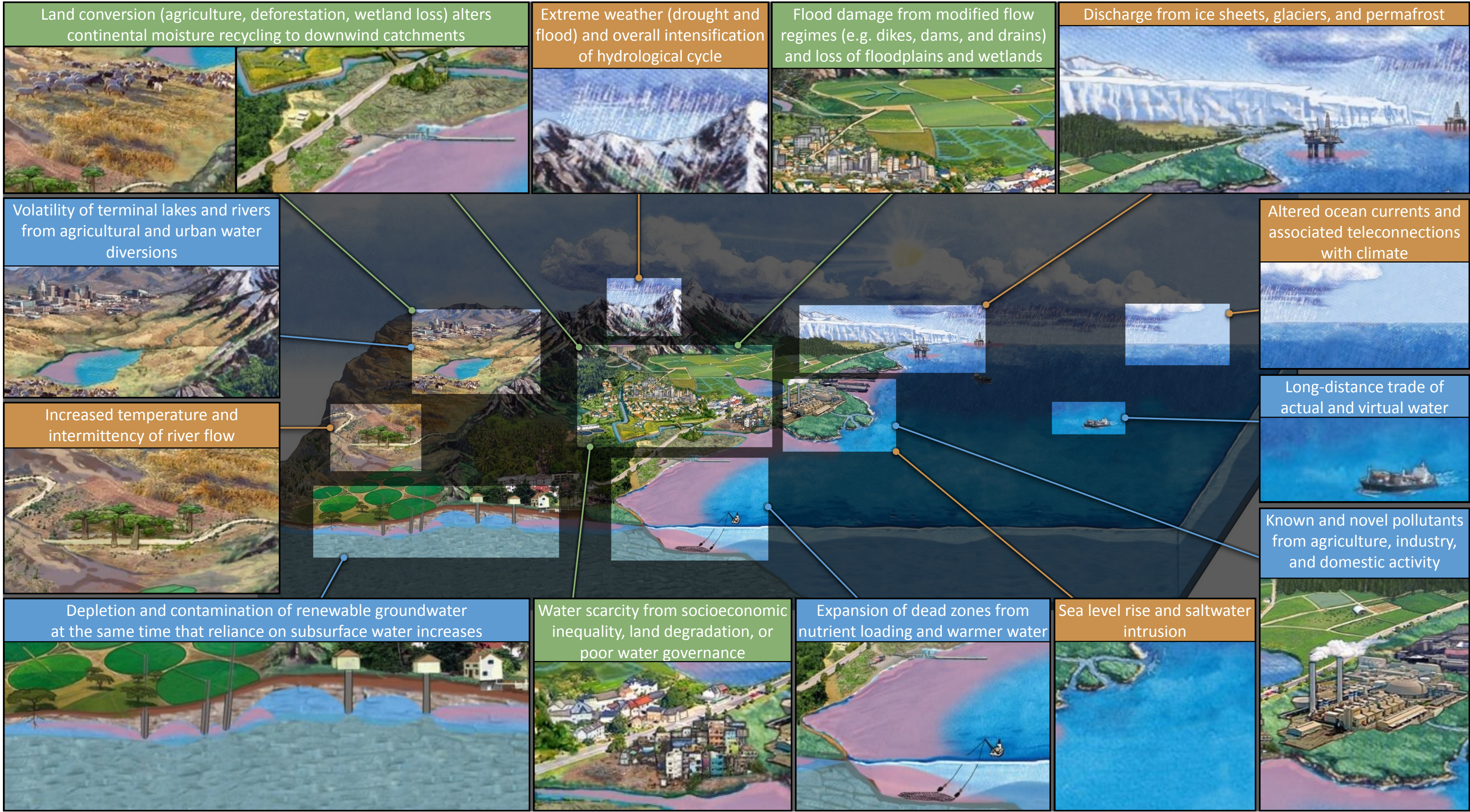


a) Major pools in the global hydrological cycle expressed in 10^3 km^3 . For panels a and b, uncertainty is expressed in $\pm \%$ based on the range of recent estimates.



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





Primary dimension of human interference: Land use Climate change Water use