

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

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

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34

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<sup>1,2</sup>. 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 cycle<sup>3-6</sup>. 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

60 concept that distant processes can have acute, local effects. Flaws in this pedagogic tool could  
61 therefore undermine efforts to promote understanding of water and general scientific thinking<sup>1,7,8</sup>.  
62 Because humans now dominate critical components of the hydrosphere<sup>9-11</sup>, and 80% of the  
63 world's population faces water insecurity or severe water scarcity<sup>12,13</sup>, improving our  
64 understanding of the global water cycle has graduated from an academic exercise to a planetary  
65 priority.

66 Human activity alters the water cycle in three distinct but interrelated ways. First, humans  
67 appropriate water through livestock, crop, and forestry use of soil moisture (green water use),  
68 water withdrawals (blue water use), and water required to assimilate pollution (gray water use;  
69 Fig. 1, Table S1)<sup>10,11,14,15</sup>. Second, humans have disturbed approximately three-quarters of the  
70 Earth's ice-free land surface through activities including agriculture, deforestation, and wetland  
71 destruction<sup>16</sup>. These disturbances alter evapotranspiration, groundwater recharge, river discharge,  
72 and precipitation at continental scales<sup>17-19</sup>. Third, climate change is disrupting patterns of water  
73 flow and storage at local to global scales<sup>20-22</sup>. These human interferences with the water cycle  
74 have confounded efforts to model regional and global water circulation<sup>18,23,24</sup>. More importantly,  
75 human activity has created a constellation of water crises that threaten billions of people and  
76 many ecosystems worldwide<sup>12,18,25-27</sup>. These regional crises of water quality, quantity, and timing  
77 have become global because they affect such a large portion of the Earth's human population and  
78 ecosystems, and because they are increasingly driven by large-scale climate change, land use, and  
79 teleconnections between water use and water availability that extend beyond the boundaries of  
80 individual catchments<sup>17,19,28</sup>.

81 Because the global water crisis is defined by human beliefs about society and nature<sup>29-32</sup>,  
82 we investigated how different research disciplines and countries conceptualize the water cycle by  
83 analyzing their representations of it. We hypothesized that diverse worldviews and scientific  
84 approaches among disciplines and countries would influence focus, detail, and

85 comprehensiveness of diagrams. We also hypothesized that advances in global hydrology<sup>9,33,34</sup>  
86 and concerted efforts to better integrate humans into our mental models of the water cycle<sup>5,6,30</sup>  
87 would improve diagrams through time. To test these hypotheses, we compiled estimates of global  
88 water pools and fluxes from more than 80 recent modelling and empirical studies, including  
89 multiple dimensions of human water use (Fig. 1; Table S1). We then collected 114 English-  
90 language diagrams of the water cycle from textbooks, peer-reviewed articles, government  
91 materials, and online sources (Methods). For each diagram, we quantified detailed metrics  
92 including biome, scientific field, and the number, magnitude, and ratios of water pools and fluxes,  
93 which we compared to our global water cycle synthesis. To analyze depiction of humans in the  
94 diagrams most accessed by the public, we then collected 350 diagrams from 12 countries using  
95 image searches in the local language.

## 96 **Reality and representation of global water pools and fluxes**

97 Our synthesis of recent water cycle studies revealed large revisions of many pool and flux  
98 estimates over the last decade, attributable to advances in remote sensing, modeling, and regional  
99 to national accounting (Fig. 1, Table S1). Perhaps most notably, new estimates of human green,  
100 blue, and gray water use now total  $\sim 24,000 \text{ km}^3 \text{ yr}^{-1}$  (Fig. 1, Table S1)<sup>10,11,14,15</sup>. This means that  
101 human freshwater appropriation redistributes the equivalent of half of global river discharge or  
102 double global groundwater recharge each year. Compared with water cycle syntheses from a  
103 decade ago<sup>30,35</sup>, recent estimates were higher for artificial reservoir storage<sup>36</sup>, non-renewable  
104 groundwater<sup>33</sup>, and groundwater recharge<sup>37</sup> but were lower for sustainably available  
105 freshwater<sup>10,14,15</sup>, renewable groundwater<sup>9,33,38</sup>, and endorheic lakes<sup>27,39</sup>. Substantial uncertainty  
106 persisted for several pools and fluxes critical to societal and ecological water needs, including  
107 groundwater, soil moisture, water in permafrost, and groundwater discharge to the ocean (Fig. 1,  
108 Table S1).

109 Despite diversity across disciplines and countries, water cycle diagrams were remarkably  
110 consistent in graphical layout. Two-thirds of diagrams showed water flowing from left to right,  
111 and only four distinct formats appeared in the whole sample (Fig. S1). There were abundant  
112 commonalities in details such as placement of landscape components and elements of the water  
113 cycle, suggesting common lineage and copying (Table S3). Sixteen unique water pools and 27  
114 unique water fluxes appeared in at least one of the 114 diagrams analyzed in detail (Table 1).  
115 With the notable exception of saline lakes, the largest 16 water pools and fluxes from our  
116 synthesis of the water cycle (Fig. 1) were depicted in at least one of the diagrams (Table 1, Fig.  
117 2). However, pool size did not influence likelihood of inclusion, with 5 of the 10 largest water  
118 pools depicted in 50% or less of diagrams (non-renewable groundwater, permafrost, saline lakes,  
119 wetlands, and soil moisture; Table 1, Fig. 2a). The depiction of water fluxes was generally more  
120 representative of reality, with the notable exceptions of the largest global water flux, ocean  
121 circulation, which appeared in only 8% of diagrams, and the third largest flux, precipitation over  
122 the ocean, which appeared in 42% (Table 1, Fig. 2b).

123 We found little support for our hypotheses that diagrams would differ by audience and  
124 vary through time (Fig 2, Table S3). Patterns in the prevalence of pools and fluxes were similar  
125 for scientific and public diagrams (Figs. S2-S5) and there were even fewer differences through  
126 time, with only 1 pool and 4 fluxes showing more than 10% difference for diagrams made before  
127 and after January 1<sup>st</sup> 2006—the chosen cutoff to separate older from newer diagrams (Fig. 2).

### 128 **Landscapes devoid of humans with abundant water**

129 Several widespread biases in water diagrams were apparent in our analysis, including  
130 under-representation of precipitation over the ocean (74% of diagrams), over-representation of  
131 temperate ecosystems from the Northern Hemisphere (92% of diagrams), exclusive focus on  
132 single-catchment dynamics (95% of diagrams), and no representation of uncertainty (99% of  
133 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<sup>27,33,39,40</sup> and approximately 97% of groundwater is non-renewable on centennial timescales  
150 (insufficient recharge or not suitable for human use due to high salinity)<sup>23,25,33,41</sup> (Fig. 3). Even  
151 quantitative diagrams typically reported the sum volume of these pools (e.g. 190,000 km<sup>3</sup> for  
152 lakes and 22,600,000 km<sup>3</sup> 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<sup>9,33</sup>. 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 use<sup>30</sup>, and only 1  
158 to 5% of fresh groundwater is sustainably extractable<sup>9,41</sup>. This means that global accessible and



159 sustainable blue water likely ranges from 5,000 to 9,000 km<sup>3</sup> yr<sup>-1</sup> <sup>10,14</sup>, coming alarmingly close to  
160 current estimates of global consumptive water use, which range from 3,800 to 5,000 km<sup>3</sup> yr<sup>-1</sup>  
161 (Table S1) <sup>11,21,42,43</sup>. Third, by excluding gray water use (water pollution), diagrams did not  
162 communicate that human activity has further diminished the small fraction of accessible and  
163 sustainable freshwater by 30 to 50% <sup>11,13,14</sup>.

## 164 **Why are diagrams still so wrong and does it matter?**

165         Diagrams of the water cycle are the central icon of hydrological sciences and one of the  
166 most visible and widespread scientific symbols in any field. These diagrams both influence and  
167 represent the understanding of researchers, educators, and policymakers <sup>8,31,44</sup>, shaping how  
168 society relates to water <sup>6,29,45</sup>. Because of their high profile, criticisms of water cycle diagrams are  
169 nearly as old as the diagrams themselves, dating at least to the 1930s when they became  
170 common <sup>31,46</sup>, and continuing to the present <sup>5</sup>. In this context, two questions arise from our analysis.  
171 Why do so many fundamental errors in global water cycle diagrams persist, and do these errors  
172 contribute to mismanagement of water?

173         Several dynamics are likely contributing to the stubborn persistence of water cycle  
174 inaccuracies. First, a practical challenge to creating an accessible and accurate representation of  
175 the water cycle is that it includes pools that vary in size by six orders of magnitude and fluxes that  
176 span five orders of magnitude (Figs. 1 and 3, Table S1). We recognize the inherent difficulty in  
177 creating an effective and attractive diagram that teaches core concepts in addition to  
178 communicating quantitative data <sup>7</sup>. Our purpose is not to nitpick the necessary simplifications and  
179 distortions associated with scientific visualizations; we wish to highlight a pervasive absence and  
180 inaccuracy: the exclusion of humans and the overrepresentation of water available for human use.  
181 Another contributing factor to the rarity of depicting human influence may be aesthetic preference  
182 for natural landscapes. Proclivity for naturalness has both cultural and evolutionary roots, which  
183 could be reinforced by industrialization and urbanization <sup>47-49</sup>, 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<sup>6,49</sup>. 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<sup>6,31</sup>. Perhaps most fundamentally, large-scale anthropogenic effects on  
193 the water cycle were less extensive and less understood a century ago<sup>18,34,50</sup>, precluding  
194 representation of land use affecting downwind catchments and other teleconnections<sup>28,51</sup>.  
195 Together, these practical, aesthetic, and historical factors may have counteracted efforts to  
196 integrate humans into depictions of the water cycle<sup>4,49</sup>.

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 vegetation<sup>3</sup>, construction of pipelines and dams<sup>52</sup>, and cloud seeding<sup>53</sup>. 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<sup>13,48,54</sup>.  
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<sup>55-57</sup>. Seasonal and  
208 interannual variability in available water is a hallmark of the hydrosphere, which will only

209 increase with climate change<sup>12,58</sup>, 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<sup>5,10</sup>. Disregard of temporal variability means that groundwater is extracted  
212 faster than it is recharged at a global scale<sup>9,23,25</sup>, terminal (endorheic) lakes and wetlands are in  
213 decline on every continent except Antarctica<sup>27,39</sup>, and semi-arid regions are experiencing  
214 desertification<sup>21,22</sup>. Third, water quality and water quantity are often treated as separate issues due  
215 to technical, legal, and disciplinary differences<sup>52,59–61</sup>. Though links between water flow and water  
216 chemistry have been understood for decades<sup>62</sup>, efforts to increase water quantity routinely trigger  
217 eutrophication of fresh and saltwater ecosystems<sup>63,64</sup>, salinization<sup>65</sup>, and ultimately reductions in  
218 useable water<sup>14,27</sup>. Fourth, much of current water management focuses on securing water supply  
219 rather than managing water demand<sup>28,32</sup>. This approach presumes that water scarcity is determined  
220 exclusively by climate and that human water use is effectively unchangeable<sup>3,51,66</sup>. 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<sup>10,28,45</sup>.

### 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<sup>10,28,49,51</sup>, loss of aquatic  
230 biodiversity<sup>13,26</sup>, climate change<sup>20,24</sup>, and freshwater and coastal eutrophication<sup>14,18</sup>. 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.

234 Beyond the obvious fixes of depicting human activity and distinguishing water that is  
235 sustainably available, several changes could substantially improve the ability of diagrams to  
236 communicate the critical concepts addressed in the previous section (Figs. 3 and 4). While 95% of  
237 the diagrams in our sample showed a single catchment, using a multi-catchment template would  
238 allow depiction of “supply-side” water dynamics, where water debits from one catchment are  
239 credits in the next via cross-continental atmospheric transport of water vapor<sup>3,28,51</sup>. This  
240 continental moisture recycling is the primary driver of terrestrial precipitation—150% larger than  
241 ocean-to-land atmospheric flux (Fig. 3). A diagram with multiple catchments allows intuitive  
242 understanding of water movement<sup>67,68</sup>, communicating the nested interactions of a global water  
243 cycle made up of many small circuits, not a single great circle (Fig. 4). More specifically, with  
244 only a single catchment to draw on, it is not possible to depict inland endorheic basins, which are  
245 extremely vulnerable to direct human disturbance, upwind alteration of evapotranspiration, and  
246 climatic shifts. Mismanagement of water in endorheic basins has caused some of the Earth’s most  
247 serious ecological, economic, and human health catastrophes<sup>18,27,39</sup>, though these woes are  
248 neglected in water cycle diagrams, none of which depict endorheic lakes. Additionally, images  
249 that reflect local socioecological conditions (Fig. 4) are more likely to engage observers and  
250 provide actionable insight to water consumers and managers<sup>5,69</sup>, enhancing coalition building and  
251 cooperative action<sup>44,70</sup>.

252 Another diagrammatic need is representation of seasonal and interannual variability in  
253 water pools and fluxes. Temporal variability in the water cycle is poorly understood by the  
254 public<sup>1,2</sup>, but change through time is indispensable to understanding hydrology because pools and  
255 fluxes such as soil moisture, river discharge, and precipitation vary by orders of magnitude on  
256 short-term, seasonal, and interannual timescales. Additionally, concepts of water security and  
257 aquatic biodiversity are only comprehensible in a framework of temporal change because they are  
258 defined by short-term extremes (e.g. droughts, floods, and biogeochemical pulses) not long-term

259 averages<sup>12-14,61</sup>. 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 systems<sup>71</sup>.

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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## REFERENCES:

1. Cardak, O. Science Students' Misconceptions of the Water Cycle According to their Drawings. *Journal of Applied Sciences* **9**, 865–873 (2009).
2. Ben-zvi-Assarf, O. & Orion, N. A study of junior high students' perceptions of the water cycle. *Journal of Geoscience Education* **53**, 366–373 (2005).
3. Ellison, D., N. Futter, M. & Bishop, K. On the forest cover-water yield debate: from demand- to supply-side thinking. *Global Change Biology* **18**, 806–820 (2012).
4. Schmidt, J. J. Historicizing the hydrosocial cycle. *Water Alternatives* **7**, 220–234 (2014).
5. Fandel, C. A., Breshears, D. D. & McMahon, E. E. Implicit assumptions of conceptual diagrams in environmental science and best practices for their illustration. *Ecosphere* **9**, 1–15 (2018).
6. Linton, J. Is the Hydrologic Cycle Sustainable? A Historical–Geographical Critique of a Modern Concept. *Annals of the Association of American Geographers* **98**, 630–649 (2008).
7. Clark, A. C. & Wiebe, E. N. Scientific Visualization for Secondary and Post–Secondary Schools. 9 (2000).
8. Harold, J., Lorenzoni, I., Shipley, T. F. & Coventry, K. R. Cognitive and psychological science insights to improve climate change data visualization. *Nature Climate Change* **6**, 1080–1089 (2016).
9. Richey, A. S. *et al.* Uncertainty in global groundwater storage estimates in a Total Groundwater Stress framework. *Water Resour. Res.* **51**, 5198–5216 (2015).
10. Rockström, J., Falkenmark, M., Lannerstad, M. & Karlberg, L. The planetary water drama: Dual task of feeding humanity and curbing climate change. *Geophys. Res. Lett.* **39**, L15401 (2012).
11. Hoekstra, A. Y. & Mekonnen, M. M. The water footprint of humanity. *PNAS* **109**, 3232–3237 (2012).
12. Mekonnen, M. M. & Hoekstra, A. Y. Four billion people facing severe water scarcity. *Science Advances* **2**, e1500323 (2016).
13. Vörösmarty, C. J. *et al.* Global threats to human water security and river biodiversity. *Nature* **467**, 555–561 (2010).
14. Heathwaite, A. L. Multiple stressors on water availability at global to catchment scales: understanding human impact on nutrient cycles to protect water quality and water availability in the long term. *Freshwater Biology* **55**, 241–257 (2010).
15. Schyns, J. F., Hoekstra, A. Y., Booij, M. J., Hogeboom, R. J. & Mekonnen, M. M. Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. *Proceedings of the National Academy of Sciences* 201817380 (2019). doi:10.1073/pnas.1817380116

- 307 16. Ellis, E. C., Klein Goldewijk, K., Siebert, S., Lightman, D. & Ramankutty, N. Anthropogenic transformation of  
308 the biomes, 1700 to 2000: Anthropogenic transformation of the biomes. *Global Ecology and Biogeography* 586–  
309 606 (2010). doi:10.1111/j.1466-8238.2010.00540.x
- 310 17. Wang-Erlandsson, L. *et al.* Remote land use impacts on river flows through atmospheric teleconnections.  
311 *Hydrology and Earth System Sciences* **22**, 4311–4328 (2018).
- 312 18. Falkenmark, M., Wang-Erlandsson, L. & Rockström, J. Understanding of water resilience in the Anthropocene.  
313 *Journal of Hydrology X* **2**, 100009 (2019).
- 314 19. Boers, N., Marwan, N., Barbosa, H. M. J. & Kurths, J. A deforestation-induced tipping point for the South  
315 American monsoon system. *Scientific Reports* **7**, 41489 (2017).
- 316 20. Durack, P. J., Wijffels, S. E. & Matear, R. J. Ocean Salinities Reveal Strong Global Water Cycle Intensification  
317 During 1950 to 2000. *Science* **336**, 455–458 (2012).
- 318 21. Haddeland, I. *et al.* Global water resources affected by human interventions and climate change. *PNAS* **111**,  
319 3251–3256 (2014).
- 320 22. Huang, J., Yu, H., Guan, X., Wang, G. & Guo, R. Accelerated dryland expansion under climate change. *Nature*  
321 *Climate Change* **6**, 166 (2016).
- 322 23. Fan, Y., Li, H. & Miguez-Macho, G. Global Patterns of Groundwater Table Depth. *Science* **339**, 940–943  
323 (2013).
- 324 24. Van Loon, A. F. *et al.* Drought in the Anthropocene. *Nature Geoscience* **9**, 89–91 (2016).
- 325 25. Famiglietti, J. S. The global groundwater crisis. *Nature Clim. Change* **4**, 945–948 (2014).
- 326 26. Creed, I. F. *et al.* Enhancing protection for vulnerable waters. *Nature Geoscience* **10**, 809 (2017).
- 327 27. Wurtsbaugh, W. A. *et al.* Decline of the world’s saline lakes. *Nature Geoscience* **10**, 816 (2017).
- 328 28. Ellison, D. *et al.* Trees, forests and water: Cool insights for a hot world. *Global Environmental Change* **43**, 51–  
329 61 (2017).
- 330 29. Falkenmark, M. Society’s interaction with the water cycle: a conceptual framework for a more holistic approach.  
331 *Hydrological Sciences Journal* **42**, 451–466 (1997).
- 332 30. Oki, T. & Kanae, S. Global Hydrological Cycles and World Water Resources. *Science* **313**, 1068–1072 (2006).
- 333 31. Linton, J. Modern water and its discontents: a history of hydrosocial renewal. *WIREs Water* **1**, 111–120 (2014).
- 334 32. Savenije, H. H. G., Hoekstra, A. Y. & van der Zaag, P. Evolving water science in the Anthropocene. *Hydrology*  
335 *and Earth System Sciences* **18**, 319–332 (2014).
- 336 33. Gleeson, T., Befus, K. M., Jasechko, S., Luijendijk, E. & Cardenas, M. B. The global volume and distribution of  
337 modern groundwater. *Nature Geoscience* **9**, 161–167 (2016).

- 338 34. Bierkens, M. F. P. Global hydrology 2015: State, trends, and directions. *Water Resources Research* **51**, 4923–  
339 4947 (2015).
- 340 35. Trenberth, K. E., Smith, L., Qian, T., Dai, A. & Fasullo, J. Estimates of the Global Water Budget and Its Annual  
341 Cycle Using Observational and Model Data. *J. Hydrometeor.* **8**, 758–769 (2007).
- 342 36. Chao, B. F., Wu, Y. H. & Li, Y. S. Impact of Artificial Reservoir Water Impoundment on Global Sea Level.  
343 *Science* **320**, 212–214 (2008).
- 344 37. Döll, P. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale  
345 assessment. *Environ. Res. Lett.* **4**, 035006 (2009).
- 346 38. Jasechko, S. *et al.* Global aquifers dominated by fossil groundwaters but wells vulnerable to modern  
347 contamination. *Nature Geosci* **10**, 425–429 (2017).
- 348 39. Wang, J. *et al.* Recent global decline in endorheic basin water storages. *Nature Geoscience* **11**, 926 (2018).
- 349 40. Messenger, M. L., Lehner, B., Grill, G., Nedeva, I. & Schmitt, O. Estimating the volume and age of water stored  
350 in global lakes using a geo-statistical approach. *Nature Communications* **7**, 13603 (2016).
- 351 41. Alley, W. M. Another Water Budget Myth: The Significance of Recoverable Ground Water in Storage. *Ground*  
352 *Water* **45**, 251–251 (2007).
- 353 42. Hanasaki, N., Inuzuka, T., Kanae, S. & Oki, T. An estimation of global virtual water flow and sources of water  
354 withdrawal for major crops and livestock products using a global hydrological model. *Journal of Hydrology* **384**,  
355 232–244 (2010).
- 356 43. Hogeboom, R. J., Knook, L. & Hoekstra, A. Y. The blue water footprint of the world’s artificial reservoirs for  
357 hydroelectricity, irrigation, residential and industrial water supply, flood protection, fishing and recreation.  
358 *Advances in Water Resources* **113**, 285–294 (2018).
- 359 44. Radinsky, J. *et al.* How planners and stakeholders learn with visualization tools: using learning sciences methods  
360 to examine planning processes. *Journal of Environmental Planning and Management* **60**, 1296–1323 (2017).
- 361 45. Wiek, A. & Larson, K. L. Water, People, and Sustainability--A Systems Framework for Analyzing and  
362 Assessing Water Governance Regimes. *Water Resources Management; Dordrecht* **26**, 3153–3171 (2012).
- 363 46. Horton, R. E. The field, scope, and status of the science of hydrology. *Eos Trans. AGU* **12**, 189–202 (1931).
- 364 47. Hagerhall, C. M., Purcell, T. & Taylor, R. Fractal dimension of landscape silhouette outlines as a predictor of  
365 landscape preference. *Journal of Environmental Psychology* **24**, 247–255 (2004).
- 366 48. Bishop, K. *et al.* Nature as the ‘Natural’ Goal for Water Management: A Conversation. *Ambio* **38**, 209–214  
367 (2009).



- 368 49. Linton, J. & Budds, J. The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water.  
369 *Geoforum* **57**, 170–180 (2014).
- 370 50. Bennett, B. M. & Barton, G. A. The enduring link between forest cover and rainfall: a historical perspective on  
371 science and policy discussions. *Forest Ecosystems* **5**, 5 (2018).
- 372 51. Keys, P. W., Wang-Erlandsson, L., Gordon, L. J., Galaz, V. & Ebbesson, J. Approaching moisture recycling  
373 governance. *Global Environmental Change* **45**, 15–23 (2017).
- 374 52. Dieter, C. A. *et al.* *Estimated use of water in the United States in 2015*. 65 (U.S. Geological Survey, 2018).
- 375 53. French, J. R. *et al.* Precipitation formation from orographic cloud seeding. *PNAS* **115**, 1168–1173 (2018).
- 376 54. Gordon, L. J. *et al.* Human modification of global water vapor flows from the land surface. *PNAS* **102**, 7612–  
377 7617 (2005).
- 378 55. Kundzewicz, Z. W. & Kaczmarek, Z. Coping with Hydrological Extremes. *Water International* **25**, 66–75  
379 (2000).
- 380 56. Grey, D. & Sadoff, C. W. Sink or Swim? Water security for growth and development. *Water Policy* **9**, 545–571  
381 (2007).
- 382 57. Wilby, R. L. *et al.* Evidence needed to manage freshwater ecosystems in a changing climate: Turning adaptation  
383 principles into practice. *Science of The Total Environment* **408**, 4150–4164 (2010).
- 384 58. Prudhomme, C. *et al.* Hydrological droughts in the 21st century, hotspots and uncertainties from a global  
385 multimodel ensemble experiment. *Proceedings of the National Academy of Sciences of the United States of*  
386 *America* **111**, 3262–3267 (2014).
- 387 59. Rodell, M. *et al.* The Observed State of the Water Cycle in the Early Twenty-First Century. *J. Climate* **28**, 8289–  
388 8318 (2015).
- 389 60. Kummerer, K., Dionysiou, D. D., Olsson, O. & Fatta-Kassinos, D. A path to clean water. *Science* **361**, 222–224  
390 (2018).
- 391 61. Abbott, B. W. *et al.* Unexpected spatial stability of water chemistry in headwater stream networks. *Ecol Lett* **21**,  
392 296–308 (2018).
- 393 62. Bormann, F. H. & Likens, G. E. Nutrient Cycling. *Science* **155**, 424–429 (1967).
- 394 63. Müller, B. *et al.* How polluted is the Yangtze river? Water quality downstream from the Three Gorges Dam.  
395 *Science of The Total Environment* **402**, 232–247 (2008).
- 396 64. Moatar, F., Abbott, B. W., Minaudo, C., Curie, F. & Pinay, G. Elemental properties, hydrology, and biology  
397 interact to shape concentration-discharge curves for carbon, nutrients, sediment, and major ions. *Water Resour.*  
398 *Res.* **53**, 1270–1287 (2017).

- 399 65. Salama, R. B., Otto, C. J. & Fitzpatrick, R. W. Contributions of groundwater conditions to soil and water  
400 salinization. *Hydrogeology Journal* **7**, 46–64 (1999).
- 401 66. Creed, I. F. & van Noordwijk, M. *Forest and Water on a Changing Planet: Vulnerability, Adaptation and*  
402 *Governance Opportunities*. 192 (2018).
- 403 67. Kastens, K. A. & Manduca. Earth and Mind II: A Synthesis of Research on Thinking and Learning in the  
404 Geosciences. *Geological Society of America* **486**, (2012).
- 405 68. Vekiri, I. What Is the Value of Graphical Displays in Learning? *Educational Psychology Review* **52** (2002).
- 406 69. Gunckel, K. L., Covitt, B. A., Salinas, I. & Anderson, C. W. A learning progression for water in socio-ecological  
407 systems. *Journal of Research in Science Teaching* **49**, 843–868 (2012).
- 408 70. Rumore, D., Schenk, T. & Susskind, L. Role-play simulations for climate change adaptation education and  
409 engagement. *Nature Climate Change* **6**, 745 (2016).
- 410 71. Su, C.-H. & Cheng, C.-H. A mobile gamification learning system for improving the learning motivation and  
411 achievements. *Journal of Computer Assisted Learning* **31**, 268–286 (2015).
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427  
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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.

459

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

466

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

470

471

## 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 1<sup>st</sup> 2006,  
510 corresponding with the publication of several high-profile papers that advocated better integration  
511 of humans into conceptualizations of the water cycle<sup>6,30,72,73</sup>. 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 <sup>74</sup>.

### 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 precipitation<sup>3</sup>), 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 <sup>6,30,75</sup>, 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 <sup>2</sup>. 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 <sup>5</sup>. Visual and numerical estimates should be  
594 accompanied by uncertainty ranges <sup>59</sup>, 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)<sup>9,33,54,76</sup>.

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 <sup>5,77</sup>. 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 <sup>71</sup>.

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**

- 614 72. Vörösmarty, C. *et al.* Humans transforming the global water system. *Eos Trans. AGU* **85**, 509–514 (2004).
- 615 73. Falkenmark, M. Heading towards basin-level hydrosolidarity goal for land/water/ecosystem coordination. *Water*  
616 *and the Environment* **12**, 178 (2005).
- 617 74. Wickham, H. *ggplot2: Elegant Graphics for Data Analysis*. (Springer New York, 2009). doi:10.1007/978-0-387-  
618 98141-3
- 619 75. Jasechko, S., Kirchner, J. W., Welker, J. M. & McDonnell, J. J. Substantial proportion of global streamflow less  
620 than three months old. *Nature Geosci* **9**, 126–129 (2016).
- 621 76. Lvovitch, M. I. The global water balance. *Eos Trans. AGU* **54**, 28–53 (1973).
- 622 77. Gombrich, E. H. Moment and Movement in Art. *Journal of the Warburg and Courtauld Institutes* **27**, 293–306  
623 (1964).

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

<b>Water pools</b> ( <i>n=114</i> )	<b>%</b>	<b>Water fluxes</b> ( <i>n=114</i> )	<b>%</b>
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
		Volcanic Steam	3
		Deposition	2
		River Discharge to Endorheic Basins	2
		Ice discharge	1
		Water loss to space	1
		Water capture from space	1
		Fog	1
<b>Human activity</b> ( <i>n=464</i> )	<b>%</b>		
Any sign of humans	23		
Humans integrated with water cycle	15		
Blue water use	10		
Green water use	3		
Gray water use (pollution)	2		
Climate change	1.4		

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

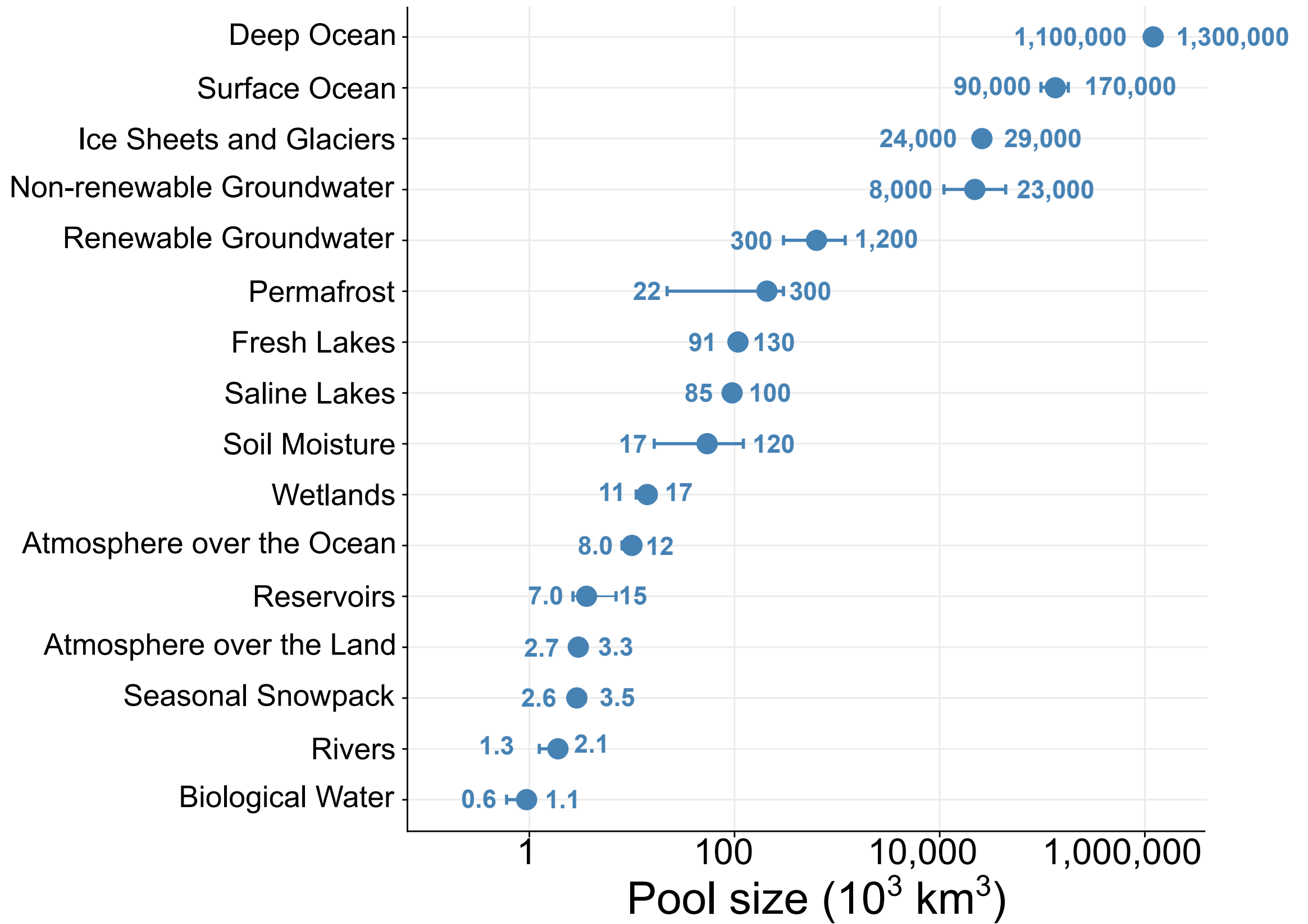
Country*	Search language	Any sign of humans	Integrated with water cycle	Green water use	Blue water use	Gray water use (pollution)	Climate change	Overlap with main sample <sup>†</sup>
France	French	43	27	0	20	0	0	10
Germany	German	47	23	0	23	0	0	20
Tunisia	Arabic	27	17	0	10	3	3	20
India	Hindi	20	17	0	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 <sup>†</sup>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.

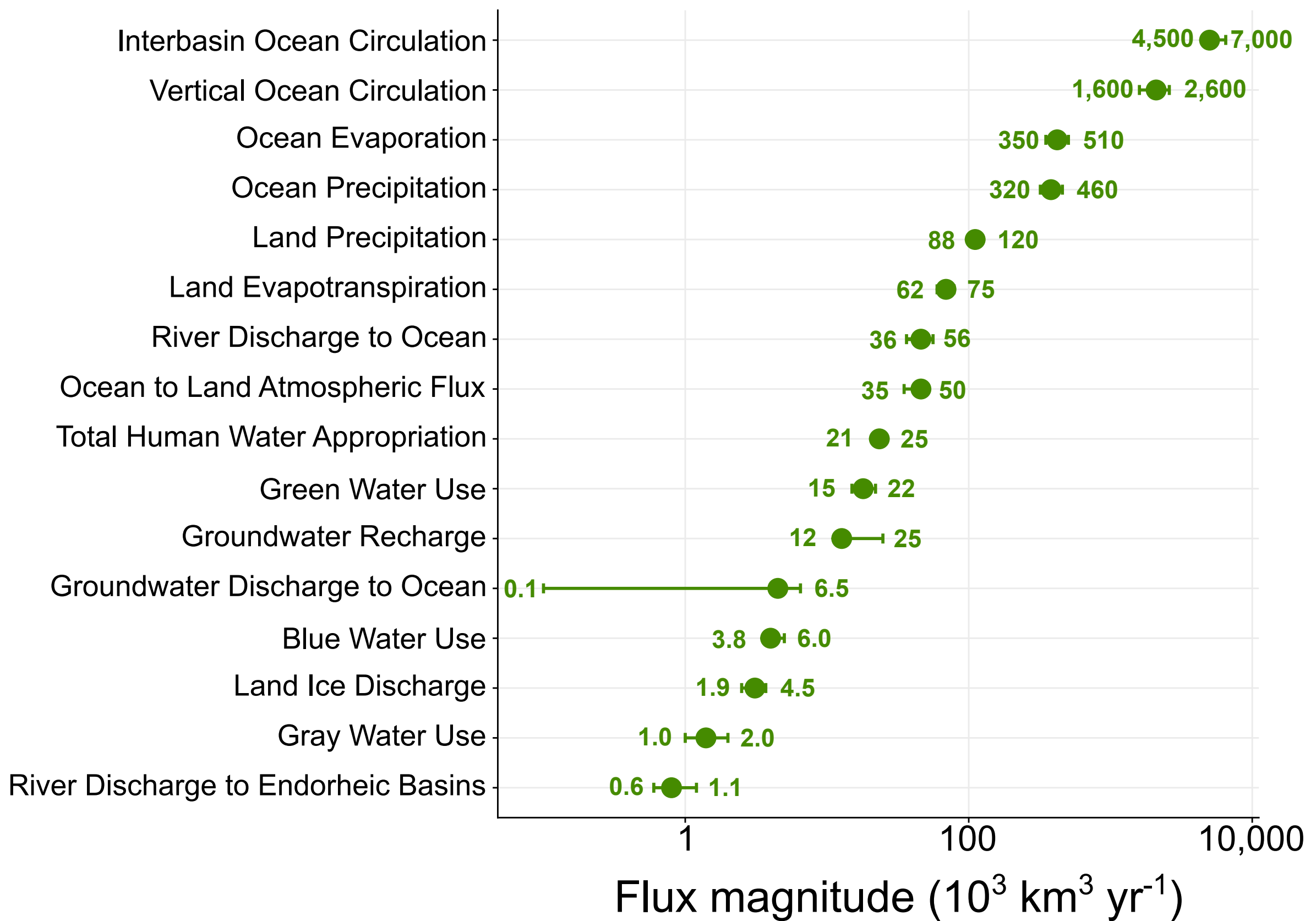
a)

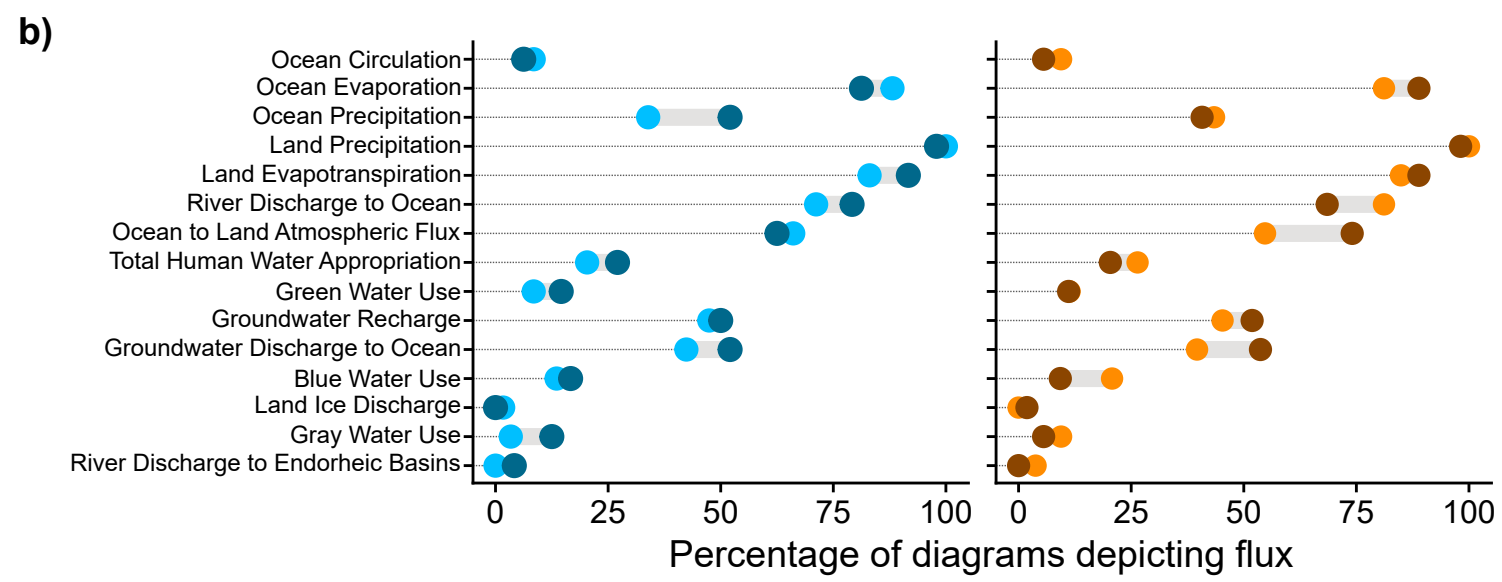
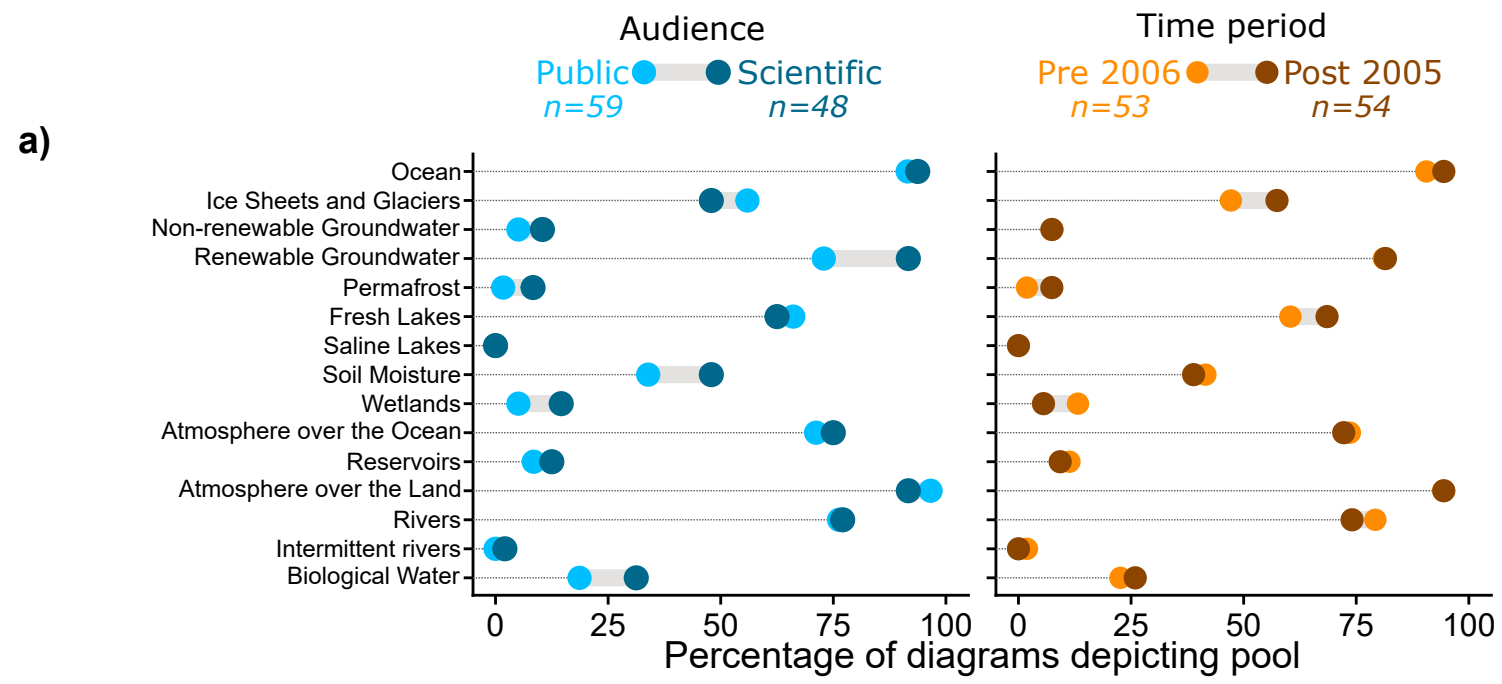
### Global water pools



b)

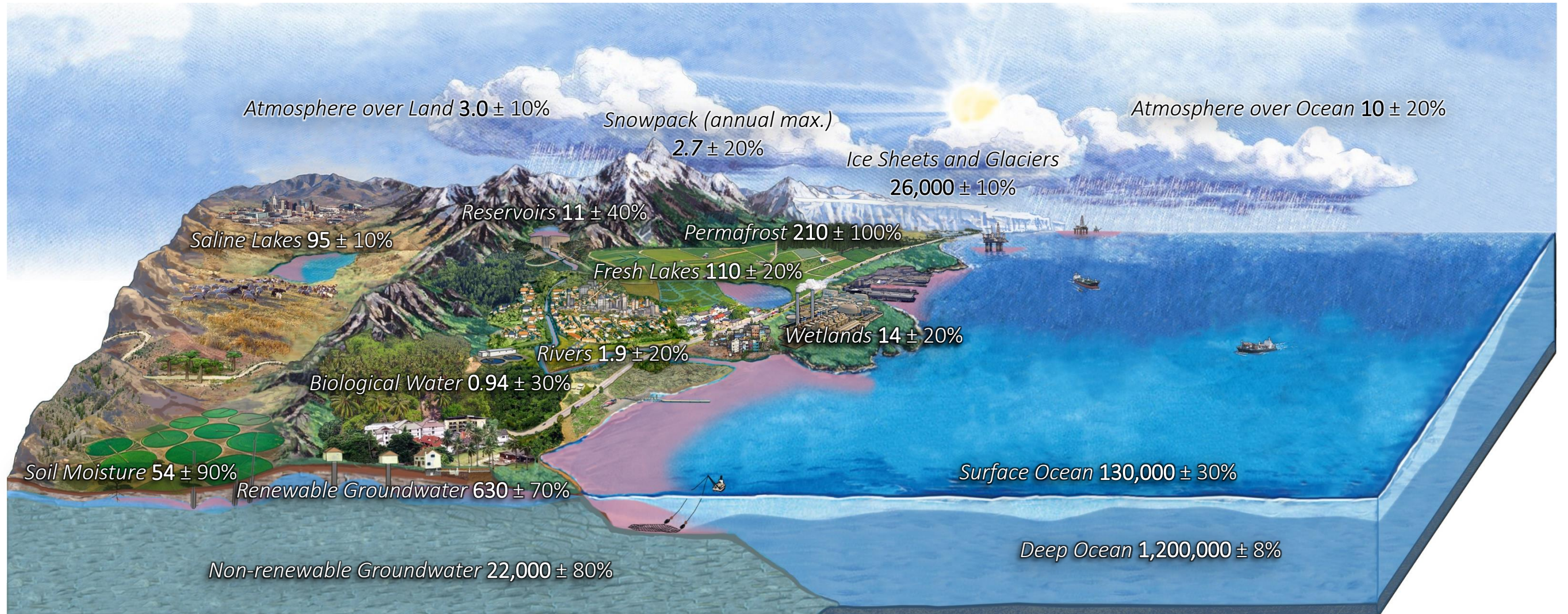
### Global water fluxes






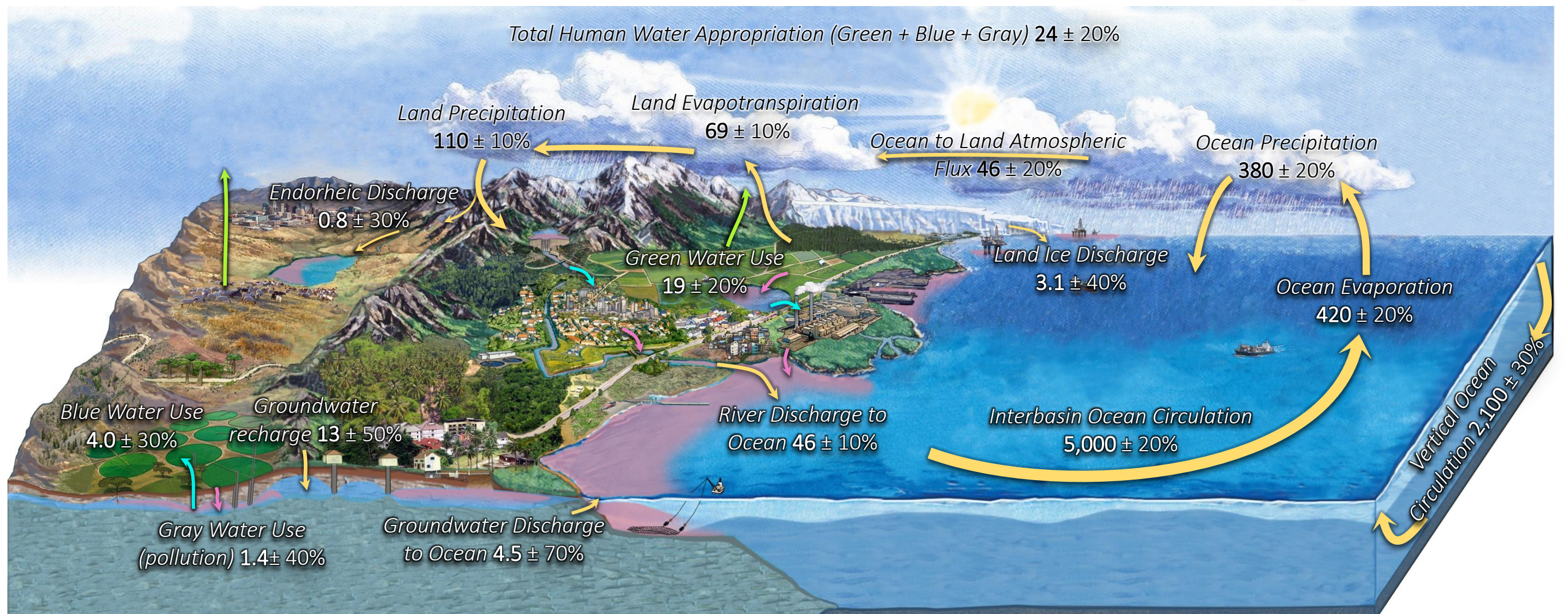


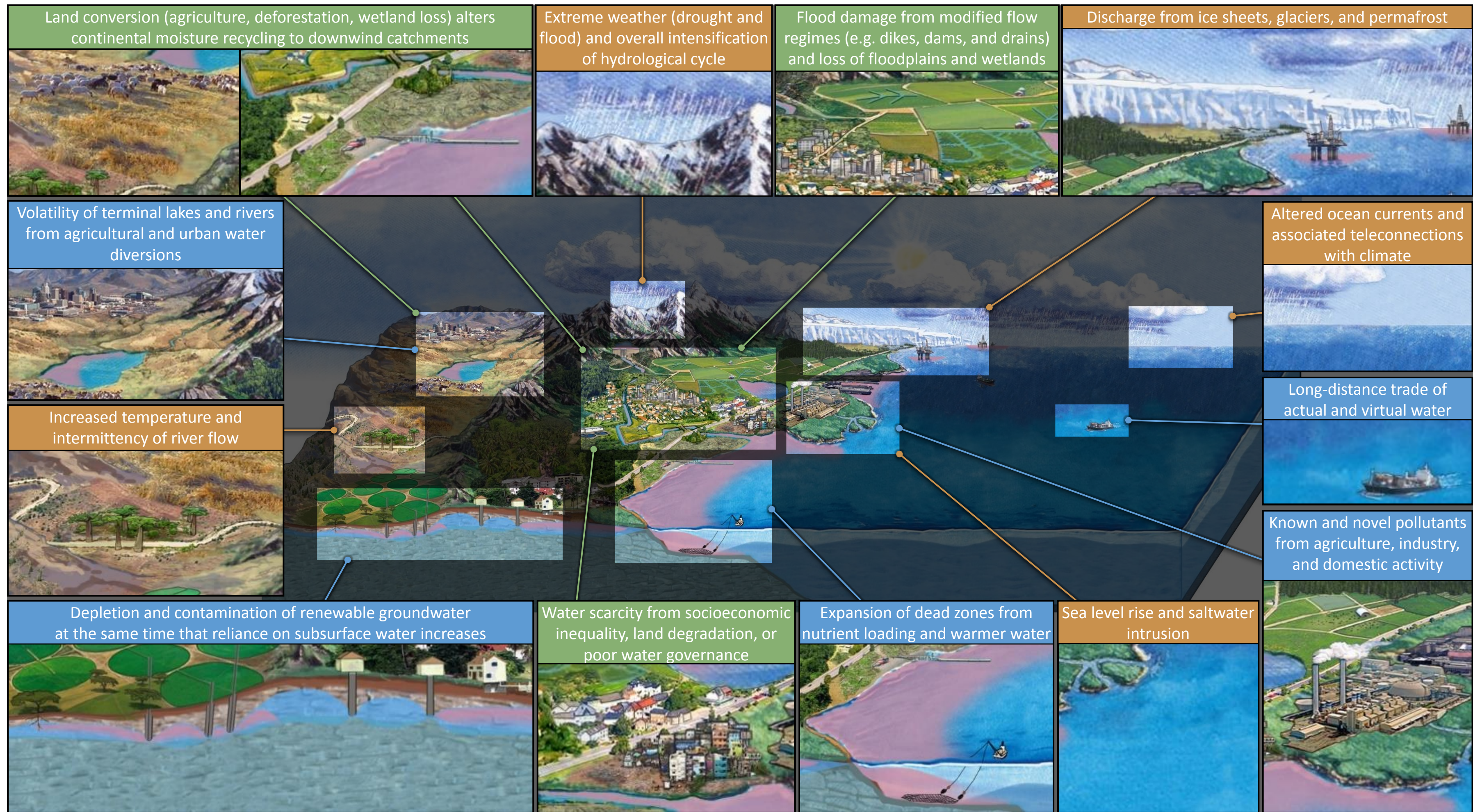


a) Major pools in the global hydrological cycle expressed in  $10^3 \text{ km}^3$ . For panels a and b, uncertainty is expressed in  $\pm \%$  based on the range of recent estimates.



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