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INVITED COMMENTARY

A water cycle for the Anthropocene

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1 | INTRODUCTION

Humour us for a minute and do an online image search of the water cycle. How many diagrams do you have to scroll through before seeing any sign of humans? What about water pollution or climate change—two of the main drivers of the global water crisis? In a recent analysis of more than 450 water cycle diagrams, we found that 85% showed no human interaction with the water cycle and 98% omitted any sign of climate change or water pollution (Abbott et al., 2019). Additionally, 92% of diagrams depicted verdant, temperate ecosystems with abundant freshwater, and 95% showed only a single river basin. It did not matter if the diagrams came from textbooks, scientific articles, or the internet, nor if they were old or new; most showed an undisturbed water cycle, free from human interference. These depictions contrast starkly with the state of the water cycle in the Anthropocene, when land conversion, human water use, and climate change affect nearly every water pool and flux (Falkenmark, Wang-Erlandsson, & Rockström, 2019; Wine & Davison, 2019; Wurtsbaugh et al., 2017). The dimensions and scale of human interference with water are manifest in failing fossil aquifers in the world's great agricultural regions (Famiglietti, 2014), accelerating ice discharge from the Arctic (Box et al., 2018), and instability in atmospheric rivers that support continental rainfall (Paul et al., 2016).

We believe that incorrect water cycle diagrams are a symptom of a much deeper and widespread problem about how humanity relates to water on Earth. Society does not understand how the water cycle works nor how humans fit into it (Abbott et al., 2019; Attari, 2014; Linton, 2014). In response to this crisis of understanding, *we call on researchers, educators, journalists, lawyers, and policy makers to change how we conceptualize and present the global water cycle.* Specifically, we must teach where water comes from, what determines its availability, and how many individuals and ecosystems are in crisis because of water mismanagement, climate change, and land conversion. Because the drivers of the global water crisis are truly global, ensuring adequate water for humans and ecosystems will require coordinated efforts that extend beyond geopolitical borders and outlast the tenure of individual administrations (Adler, 2019; Keys, Wang-Erlandsson, Gordon, Galaz, & Ebbesson, 2017). This level of coordination and holistic thinking requires widespread understanding of the water cycle and the global water crisis. Making the causes and consequences of the water crisis visible in our diagrams is a tractable and important step towards the goal of a sustainable relationship with water that includes ecosystems and society.

2 | A FAILING ICON

The diagram of the water cycle is a central icon of Earth and environmental sciences. For many people, it is the point of entry into thinking about critical scientific concepts such as conservation of mass, ecological interconnectedness, and human dependence and influence on Earth's great cycles. Since the concept of the modern water cycle emerged in the early 1900s (Linton, 2014; Linton & Budds, 2014), water cycle diagrams have emphasized natural landscapes and a primarily vertical water cycle: evaporation from surface water followed by precipitation over the land (Duffy, 2017; Fandel, Breshears, & McMahon, 2018). In reality, the primary source of terrestrial precipitation that supports all continental life is the land, not the ocean as depicted in diagrams (Ellison, Futter, & Bishop, 2012). Earth's water cycle is not a single great circle; it is a series of loops linked by terrestrial water recycling and therefore vulnerable to changes in land use and water use (Boers, Marwan, Barbosa, & Kurths, 2017; Wang-Erlandsson et al., 2018). With this perspective, human interference with the water cycle is much more than just water consumption; it includes land conversion and climate change (Figure 1), which alter both vertical water flow to the

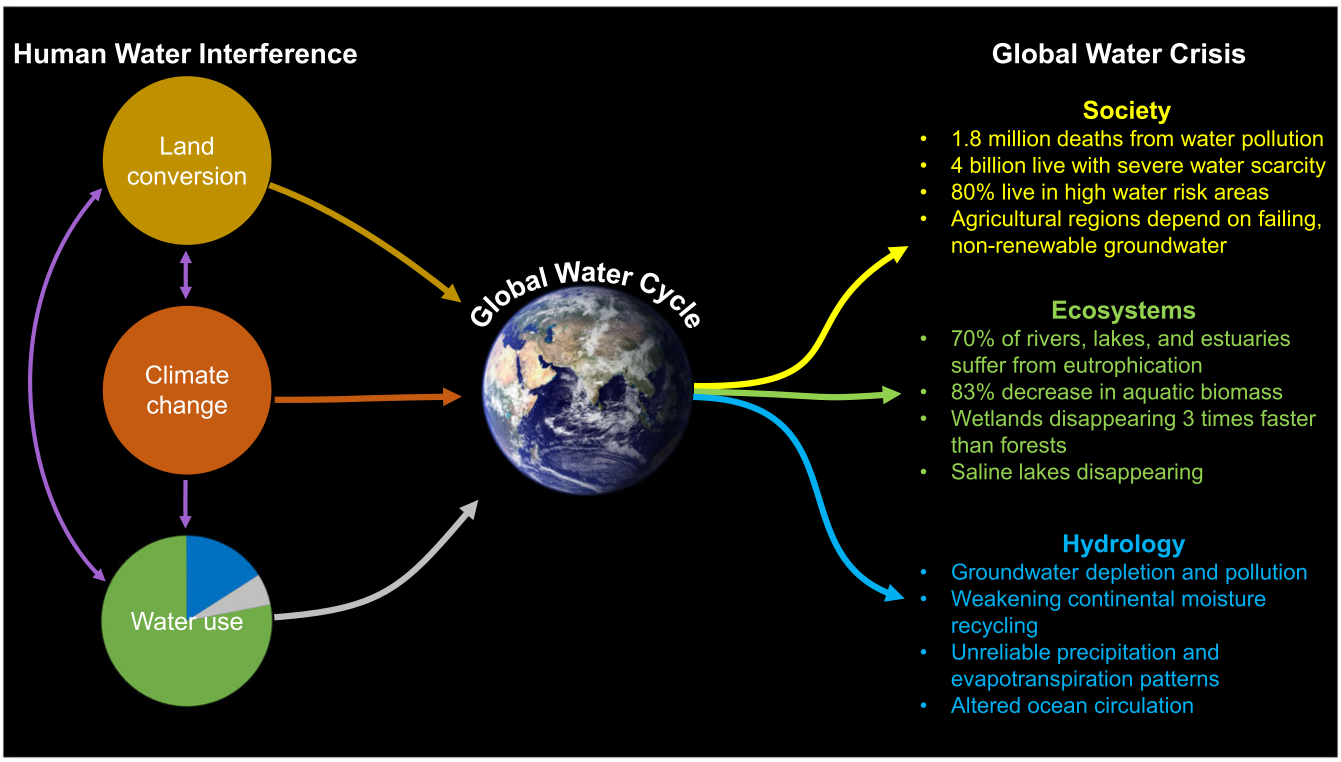

FIGURE 1 Types of human interference with the global water cycle and dimensions of the global water crisis. Human water use is separated into green (78%), blue (16%), and grey water use (6%) based on a meta-analysis of global water pools and fluxes (Abbott et al., 2019)

atmosphere and lateral movement across, above, and underneath land and water surfaces (DeAngelis et al., 2010; Durack, Wijffels, & Matear, 2012; Falkenmark et al., 2019).

Some might accuse us of expecting too much of water cycle diagrams. After all, does it matter that diagrams are wrong if researchers and policy makers understand the drivers of the water cycle and the water crisis? Given the difficulties of depicting global hydrology in the Anthropocene, one could argue that we are just bullying a beloved and trusted scientific symbol. Indeed, more than one reviewer of our work argued, in effect, that "this is an interesting analysis, but everyone knows that humans affect the water cycle, so these details are not particularly troubling."

We believe that dismissing inaccuracies in water cycle drawings as inevitable or unimportant is problematic for several reasons. First, the exclusion of human activity is not a simplification; it is an omission that renders the hydrological cycle incomprehensible in the Anthropocene. It is no longer possible to understand the space–time distribution of water quantity and quality on Earth without considering human activity (Falkenmark et al., 2019; Linton & Budds, 2014; Van Loon et al., 2016). Human alteration of water, land, and climate have so severely altered the water cycle that model simulations based solely on natural dynamics no longer reliably predict groundwater levels, droughts, floods, or precipitation (Abbott et al., 2019; Bradshaw, Sodhi, Peh, & Brook, 2007; Paul et al., 2016; van Dijk et al., 2013). Second, although researchers in hydrology may have the knowledge to interpret and challenge incorrect visualizations of the water cycle, most people assume scientific diagrams are correct. Everyone interacts with water from birth, but our individual experiences are intensely personal—the water we wash ourselves with, give our children, and run from during a rainstorm. Because we cannot directly observe large-scale hydrological processes, we rely on water cycle diagrams to convey a correct understanding of the global water cycle. Third and most fundamentally, misconceptions of water in the Anthropocene extend far beyond popular diagrams of the water cycle. Some of the highest-profile scientific publications only consider consumptive water use when determining sustainable planetary limits for freshwater (Steffen et al., 2015), and others present terrestrial evaporation and transpiration as water losses (Schyns, Hoekstra, Booij, Hogeboom, & Mekonnen, 2019) rather than the primary sources of freshwater for agriculture and ecosystems (Ellison et al., 2012; Heistermann, 2017; van Noordwijk & Ellison, 2019).

3 | THE INVISIBLE GLOBAL WATER CRISIS

Water is the defining characteristic of our planet, and the water cycle operates on a scale so immense that we describe it in thousands of cubic kilometres or trillions of metric tons. The sheer size of the Earth's water cycle can give the impression that human activity could never alter it. However, in the Anthropocene, humans have reshaped the water cycle in three connected ways (Figures 1 and 2). First, virtually, every agricultural, industrial, and domestic activity uses water directly and indirectly. This water use is classified as green (soil moisture used by human livestock and crops), blue (direct transport and consumption of water), and grey (water used to dilute human pollutants), which together exceed global groundwater recharge (Döll & Fiedler, 2008; Gleeson, Befus, Jasechko, Luijendijk, & Cardenas, 2016) or the equivalent of half of all the water running from land to sea—24,400 km^3 each year ± 20% (Abbott et al., 2019). Human water use is sustainable for some regions at some times, but for large portions of the globe, groundwater pumping exceeds recharge, river discharge is overallocated, and water pollution (grey water use) causes rampant human disease and ecosystem degradation (Dupas, Minaudo, & Abbott, 2019; Falkenmark et al., 2019; Landrigan et al., 2017). Second, humans have directly modified 77% of the Earth's land surface, excluding Antarctica, through activities such as agriculture, deforestation, and wetland destruction (Watson et al., 2018). Land use alters evapotranspiration, groundwater recharge, and run-off within and beyond catchments in surprising ways. For example, large-scale deforestation has weakened the monsoon rains in India (Paul et al., 2016) and South America (Boers et al., 2017), fossil groundwater extraction in the central United States has increased downwind precipitation by 15–30% during the peak growing season (DeAngelis et al., 2010), and water flow in many of the world's great rivers has been influenced by land use change outside of the rivers' own basins (Gebrehiwot et al., 2019; Keys et al., 2012; Wang-Erlandsson et al., 2018). Third, climate change is altering nearly every water pool and flux, including ocean circulation, land ice discharge, precipitation timing and intensity, drought, flooding, and evapotranspiration (Abbott et al., 2019; Falkenmark et al., 2019; Famiglietti, 2014; Huang, Yu, Guan, Wang, & Guo, 2016).

Do these issues qualify as a singular global water crisis, and does it matter if they are missing from our water cycle diagrams? We say yes on both counts. Water cycle diagrams are iconic symbols of our understanding of water on Earth and are among the most visible communication tools in all of science. The fact that the global water crisis is invisible in nearly all water cycle diagrams is troubling on its own, yet we have found that this erasure extends into the perceptions of some scientists and of the public. Several critics of our work evaluating diagrams questioned the severity and scale of water crises, with one reviewer stating "I was not aware that there is a general agreement on the existence of a global water crisis … I recommend abstaining from such assessments." If there is no scientific consensus that a global water crisis even exists (Steffen et al., 2015), how can we mobilize the resources and collective will to address it? With or without scientific approval, 1.8 million people die every year from polluted water (Landrigan et al., 2017), tens of thousands die from flooding (Bradshaw et al., 2007; Dottori et al., 2018), most of the Earth's population experiences severe water scarcity (Mekonnen & Hoekstra, 2016; Vörösmarty et al., 2010), freshwater species have declined by more than 80% (Harrison et al., 2018), two-thirds of the Earth's rivers, lakes, and estuaries are experiencing eutrophication because of anthropogenic nutrient loading (Kolbe et al., 2019; Le Moal et al., 2019), and many of the world's great agricultural regions depend on non-renewable groundwater, which is being depleted at an accelerating pace (Famiglietti, 2014; Richey et al., 2015). The water crisis is

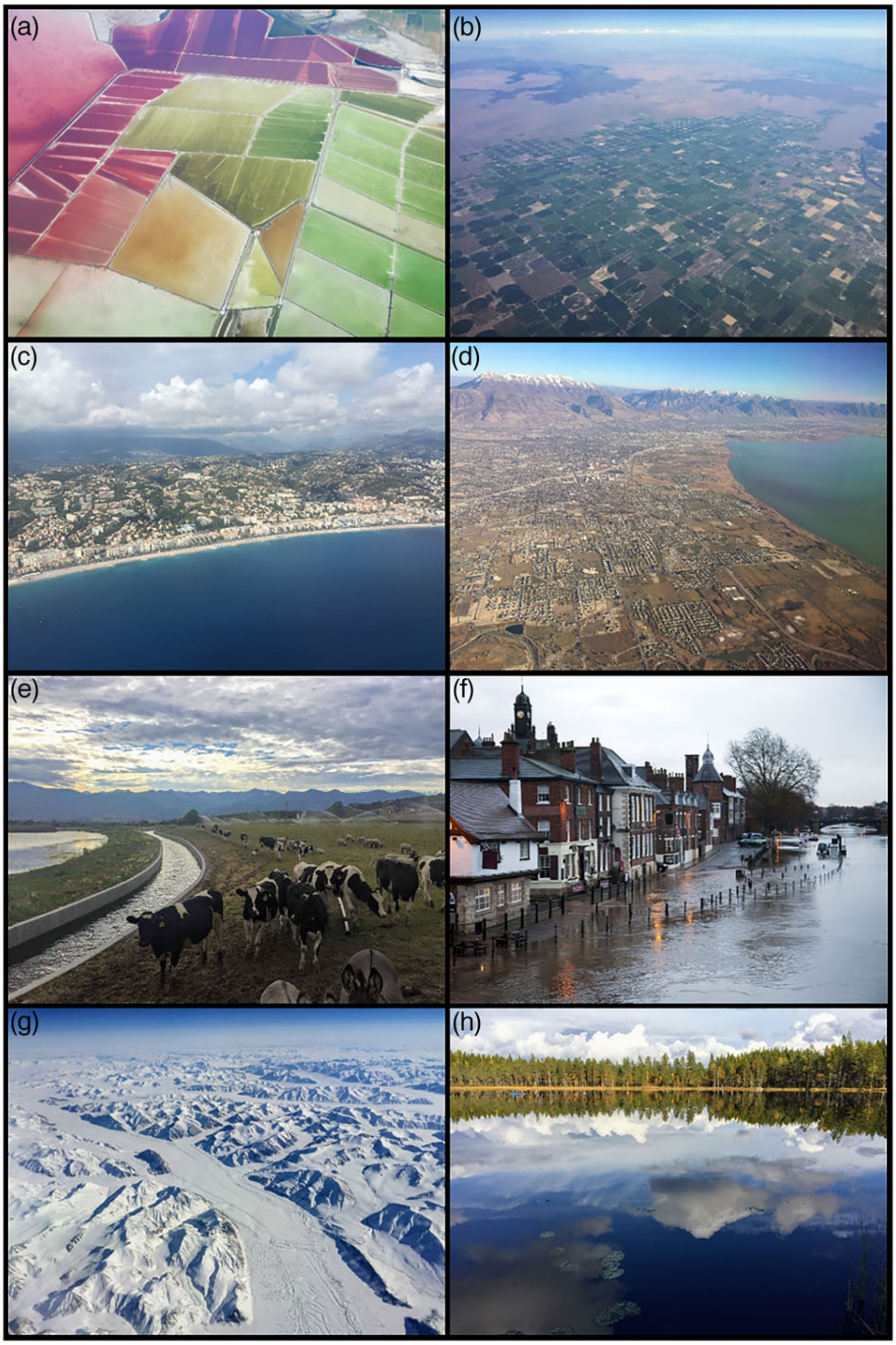

FIGURE 2 Photos of human interactions with the water cycle in the Anthropocene. (a) Evaporation ponds encroach on the Great Salt Lake, the largest saline lake in the Western Hemisphere, USA; (b) Groundwater-fed agriculture and human-caused wildfire, Washington, USA; (c) Urban development along the coast in Nice, France. (d) Suburban sprawl sustained by inter-basin water transfer around Utah Lake, USA; (e) Livestock, canal, and irrigation in Heber City, USA; Flooding as the River Ouse in York exceeds defensive engineering infrastructure, UK; (g) Accelerating ice discharge from northern Greenland; (h) Boreal lake experiencing thermal and chemical modification from atmospheric deposition and climate change, Västerbotten, Sweden

truly global because of the number of people and ecosystems it affects and because its tangled causes—land use, climate change, and water use—now extend beyond the boundaries of individual regions or countries. The reluctance of some to acknowledge the global water crisis is itself a failure of past and current water paradigms.

4 | BETTER WATER DIAGRAMS AND POLICY IN THE ANTHROPOCENE

Besides putting humans back in the picture, what can be done to improve water cycle diagrams? Two of the challenges in depicting and managing water are inherent to systems science: temporal variation and spatial interactions. Temporal variability is critical to understanding the concepts of water security, flooding, and aquatic habitat, which are defined by occasional extremes more than average conditions (Abbott et al., 2018; Dottori et al., 2018; Prudhomme et al., 2014). Many of the most important water pools and fluxes for ecosystems and society, including soil water, precipitation, and river flow, experience rapid fluctuations seasonally and annually. Others, like terrestrial water recycling and non-renewable groundwater, initially respond slowly to human pressure, allowing expansion of civilizations and associated water demand before abruptly collapsing or changing after an unanticipated threshold is exceeded (Ellison et al., 2012;

Falkenmark et al., 2019; Heistermann, 2017). New media formats including interactive water cycle games or multi-panel diagrams could better communicate these central water truths (Abbott et al., 2019).

Spatial interactions in the water cycle are similarly difficult to predict and control. Water flow through and across the Earth's surface is determined by topographic watersheds, but water inputs depend on atmospheric transport of water vapour from upwind airsheds (Keys et al., 2012). Nearly all the diagrams we analysed showed a single watershed, precluding the larger-scale interactions that connect all parts of the global water cycle (Abbott et al., 2019), such as how deforestation in West African threatens Nile River flows and, thus, Egypt's water supply (Gebrehiwot et al., 2019). Similarly, most water policies and practices are based on single-catchment perspectives, where trees "use" water and evapotranspiration is viewed as a loss. Disregarding water transport from outside the watershed boundaries can lead to questionable interventions such as cloud seeding, removal of vegetation, and inter-basin pipeline construction (Ellison et al., 2012; van Noordwijk & Ellison, 2019). These engineering "solutions" not only are costly and ineffective but also can exacerbate water scarcity and undermine sustainable development goals by diverting water from downstream or downwind communities, producing unintended or unknown side-effects, and reducing resilience to natural and anthropogenic variability (Abbott et al., 2019; Falkenmark et al., 2019; Linton & Budds, 2014).

Another key message for water diagrams in the Anthropocene must be how much, or rather how little water is available for humans and ecosystems. Diagrams currently over-represent freshwater availability by showing abundant water sources with no consideration of water chemistry or availability. Half of global lake water is saline, and more than 97% of groundwater is not useable because of salinity, age, or surface collapse, though water diagrams show that the totality of these pools is fresh and available for human use (Abbott et al., 2019). Additionally, water pollution has further decreased the fraction of available freshwater by 30% to 50% globally and much more for many regions (Abbott et al., 2019). Emphasizing the finite and fragile nature of freshwater resources could help us graduate from fixating solely on increasing supply to managing demand (Qin et al., 2019)—a transition that is needed critically in many regions experiencing water stress due to luxury water use such as decorative lawns and excess meat and dairy production.

5 | GLOBAL HYDROLOGY FOR GLOBAL PROBLEMS

For historical, aesthetic, and disciplinary reasons (Duffy, 2017; Fandel et al., 2018; Linton & Budds, 2014), we continue to teach that interaction with the global water cycle is a one-way street: the water cycle affects us, not the other way around. Given the enormity of the global water crisis, we propose that there is no good excuse for excluding humans from depictions of the water cycle, no matter the scale or purpose of the drawing. As water researchers and educators, we should emulate other disciplines that more effectively depict human interactions with their study systems. For example, contrast the disciplinary way we teach the water cycle with the integrated way ecosystem ecologists teach the carbon and nitrogen cycles, where human activity is almost always depicted in diagrams (Abbott et al., 2019).

Currently, there is not only a mismatch in space between the size of the drivers of precipitation and the limits of sovereign governments, there is also a mismatch in time between the frequency of hydrological variation and changes in political power. The Earth's ecosystems, including human society, are facing a global water crisis, but most of us are not equipped to answer the fundamental question of where rain comes from. Unfortunately, you could not find the correct answer to that question in most water cycle diagrams.

As a research and education community, we must create and disseminate a new generation of water cycle diagrams that integrate the dimensions of human–water interactions and accurately reflect the state of our knowledge of global hydrology. These diagrams should emphasize spatial linkages and temporal variation to teach how water availability depends on large-scale and long-term conservation of natural ecosystems. Diagrams that effectively teach how nested connections influence water availability in specific geographic places will better support nature-based solutions (Bishop et al., 2009), which are more likely to establish water practices that are ecologically and socio-politically sustainable (Fandel et al., 2018; Gunckel, Covitt, Salinas, & Anderson, 2012).

At this time, when human disruption of the water cycle threatens ecosystems and society more than ever, we need to reconceive our relationship with water. Our disciplinary approach to hydrology as a matter of fluid dynamics and physical heterogeneity has generated great understanding but has failed to protect ecosystems and ensure sustainable water resource development and equitable water governance (Sivapalan, 2018). The latter is critical to achieving UN Sustainable Development Goal 6—clean water and sanitation for all by 2030. The diagrams that should communicate the most precious precepts in hydrology are currently obstacles that obscure crucial truths about the hydrosocial cycle in the Anthropocene (Linton & Budds, 2014). Although we know that correcting visualizations of the water cycle will not solve the global water crisis on its own, rehabilitating this iconic symbol of a fundamental Earth system is a step towards awareness and sustainable participation of humanity in the global water cycle.

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REFERENCES

Abbott, B. W., Bishop, K. H., Zarnetske, J. P., Minaudo, C., Chapin, F. S., Krause, S., … Pinay, G. (2019). Human domination of the global water cycle absent from depictions and perceptions. *Nature Geoscience*, *12*, 533–540. https://doi.org/10.1038/s41561-019-0374-y

Abbott, B. W., Gruau, G., Zarnetske, J. P., Moatar, F., Barbe, L., Thomas, Z., … Pinay, G. (2018). Unexpected spatial stability of water chemistry in headwater stream networks. *Ecology Letters*, *21*(2), 296–308. https://doi.org/10.1111/ele.12897

Adler, R. W. (2019). Coevolution of law and science. *Columbia Journal of Environmental Law*, *44*(1), 1–66. https://doi.org/10.7916/cjel.v44i1.805

Attari, S. Z. (2014). Perceptions of water use. *Proceedings of the National Academy of Sciences*, *111*(14), 5129–5134. https://doi.org/10.1073/pnas.1316402111

Bishop, K., Beven, K., Destouni, G., Abrahamsson, K., Andersson, L., Johnson, R. K., … Hjerdt, N. (2009). Nature as the 'natural' goal for water management: A conversation. *Ambio*, *38*(4), 209–214. https://doi.org/10.1579/0044-7447-38.4.209

Boers, N., Marwan, N., Barbosa, H. M. J., & Kurths, J. (2017). A deforestation-induced tipping point for the South American monsoon system. *Scientific Reports*, *7*, 41489. https://doi.org/10.1038/srep41489

Box, J. E., Colgan, W. T., Wouters, B., Burgess, D. O., O'Neel, S., Thomson, L. I., & Mernild, S. H. (2018). Global sea-level contribution from Arctic land ice: 1971–2017. *Environmental Research Letters*, *13*(12), 125012. https://doi.org/10.1088/1748-9326/aaf2ed

Bradshaw, C. J. A., Sodhi, N. S., Peh, K. S.-H., & Brook, B. W. (2007). Global evidence that deforestation amplifies flood risk and severity in the developing world. *Global Change Biology*, *13*(11), 2379–2395. https://doi.org/10.1111/j.1365-2486.2007.01446.x

DeAngelis, A., Dominguez, F., Fan, Y., Robock, A., Kustu, M. D., & Robinson, D. (2010). Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States. *Journal of Geophysical Research-Atmospheres*, *115*(D15), D15115. https://doi.org/10.1029/2010JD013892

Döll, P., & Fiedler, K. (2008). Global-scale modeling of groundwater recharge. *Hydrology and Earth System Sciences*, *12*(3), 863–885. https://doi.org/10.5194/hess-12-863-2008

Dottori, F., Szewczyk, W., Ciscar, J.-C., Zhao, F., Alfieri, L., Hirabayashi, Y., … Feyen, L. (2018). Increased human and economic losses from river flooding with anthropogenic warming. *Nature Climate Change*, *8*(9), 781–786. https://doi.org/10.1038/s41558-018-0257-z

Duffy, C. J. (2017). The terrestrial hydrologic cycle: An historical sense of balance. *Wiley Interdisciplinary Reviews Water*, *4*, n/a–n/a. https://doi.org/10.1002/wat2.1216

Dupas, R., Minaudo, C., & Abbott, B. W. (2019). Stability of spatial patterns in water chemistry across temperate ecoregions. *Environmental Research Letters*, *14*(7). https://doi.org/10.1088/1748-9326/ab24f4

Durack, P. J., Wijffels, S. E., & Matear, R. J. (2012). Ocean Salinities reveal strong global water cycle intensification during 1950 to 2000. *Science*, *336*(6080), 455–458. https://doi.org/10.1126/science.1212222

Ellison, D., Futter, M. N., & Bishop, K. (2012). On the forest cover-water yield debate: From demand- to supply-side thinking. *Global Change Biology*, *18*(3), 806–820. https://doi.org/10.1111/j.1365-2486.2011.02589.x

Falkenmark, M., Wang-Erlandsson, L., & Rockström, J. (2019). Understanding of water resilience in the Anthropocene. *Journal of Hydrology X*, *2*, 100009. https://doi.org/10.1016/j.hydroa.2018.100009

Famiglietti, J. S. (2014). The global groundwater crisis. *Nature Climate Change*, *4*(11), 945–948. https://doi.org/10.1038/nclimate2425

Fandel, C. A., Breshears, D. D., & McMahon, E. E. (2018). Implicit assumptions of conceptual diagrams in environmental science and best practices for their illustration. *Ecosphere*, *9*(1), 1–15. https://doi.org/10.1002/ecs2.2072

Gebrehiwot, S. G., Ellison, D., Bewket, W., Seleshi, Y., Inogwabini, B.-I., & Bishop, K. (2019). The Nile Basin waters and the West African rainforest: Rethinking the boundaries. *Wiley Interdisciplinary Reviews Water*, *6*(1), e1317. https://doi.org/10.1002/wat2.1317

Gleeson, T., Befus, K. M., Jasechko, S., Luijendijk, E., & Cardenas, M. B. (2016). The global volume and distribution of modern groundwater. *Nature Geoscience*, *9*(2), 161–167. https://doi.org/10.1038/ngeo2590

Gunckel, K. L., Covitt, B. A., Salinas, I., & Anderson, C. W. (2012). A learning progression for water in socio-ecological systems. *Journal of Research in Science Teaching*, *49*(7), 843–868. https://doi.org/10.1002/tea.21024

Harrison, I., Abell, R., Darwall, W., Thieme, M. L., Tickner, D., & Timboe, I. (2018). The freshwater biodiversity crisis. *Science*, *362*(6421), 1369–1369. https://doi.org/10.1126/science.aav9242

Heistermann, M. (2017). HESS Opinions: A planetary boundary on freshwater use is misleading. *Hydrology and Earth System Sciences*, *21*(7), 3455–3461. https://doi.org/10.5194/hess-21-3455-2017

Huang, J., Yu, H., Guan, X., Wang, G., & Guo, R. (2016). Accelerated dryland expansion under climate change. *Nature Climate Change*, *6*(2), 166–171. https://doi.org/10.1038/nclimate2837

Keys, P. W., van der Ent, R. J., Gordon, L. J., Hoff, H., Nikoli, R., & Savenije, H. H. G. (2012). Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. *Biogeosciences*, *9*(2), 733–746. https://doi.org/10.5194/bg-9-733-2012

Keys, P. W., Wang-Erlandsson, L., Gordon, L. J., Galaz, V., & Ebbesson, J. (2017). Approaching moisture recycling governance. *Global Environmental Change*, *45*, 15–23. https://doi.org/10.1016/j.gloenvcha.2017.04.007

Kolbe, T., de Dreuzy, J.-R., Abbott, B. W., Aquilina, L., Babey, T., Green, C. T., … Pinay, G. (2019). Stratification of reactivity determines nitrate removal in groundwater. *Proceedings of the National Academy of Sciences*, *116*, 2494–2499. https://doi.org/10.1073/pnas.1816892116

Landrigan, P. J., Fuller, R., Acosta, N. J. R., Adeyi, O., Arnold, R., Basu, N., … Zhong, M. (2017). The Lancet Commission on pollution and health. *The Lancet*, *391*, 462–512. https://doi.org/10.1016/S0140-6736(17)32345-0

Le Moal, M., Gascuel-Odoux, C., Ménesguen, A., Souchon, Y., Étrillard, C., Levain, A., … Pinay, G. (2019). Eutrophication: A new wine in an old bottle? *Science of the Total Environment*, *651*, 1–11. https://doi.org/10.1016/j.scitotenv.2018.09.139

Linton, J. (2014). Modern water and its discontents: A history of hydrosocial renewal. *Wiley Interdisciplinary Reviews Water*, *1*(1), 111–120. https://doi.org/10.1002/wat2.1009

Linton, J., & Budds, J. (2014). The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water. *Geoforum*, *57*, 170–180. https://doi.org/10.1016/j.geoforum.2013.10.008

Mekonnen, M. M., & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. *Science Advances*, *2*(2), e1500323. https://doi.org/10.1126/sciadv.1500323

Paul, S., Ghosh, S., Oglesby, R., Pathak, A., Chandrasekharan, A., & Ramsankaran, R. (2016). Weakening of Indian summer monsoon rainfall due to changes in land use land Cover. *Scientific Reports*, *6*, 32177. https://doi.org/10.1038/srep32177

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N. W., Dankers, R., … Wisser, D. (2014). Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(9), 3262–3267. https://doi.org/10.1073/pnas.1222473110

Qin, Y., Mueller, N. D., Siebert, S., Jackson, R. B., AghaKouchak, A., Zimmerman, J. B., … Davis, S. J. (2019). Flexibility and intensity of global water use. *Nature Sustainability*, *2*, 515–523. https://doi.org/10.1038/s41893-019-0294-2

Richey, A. S., Thomas, B. F., Lo, M.-H., Famiglietti, J. S., Swenson, S., & Rodell, M. (2015). Uncertainty in global groundwater storage estimates in a Total Groundwater Stress framework. *Water Resources Research*, *51*(7), 5198–5216. https://doi.org/10.1002/2015WR017351

Schyns, J. F., Hoekstra, A. Y., Booij, M. J., Hogeboom, R. J., & Mekonnen, M. M. (2019). Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. *Proceedings of the National Academy of Sciences*: 201817380, *116*, 4893–4898. https://doi.org/10.1073/pnas.1817380116

Sivapalan, M. (2018). From engineering hydrology to Earth system science: Milestones in the transformation of hydrologic science. *Hydrology and Earth System Sciences*, *22*(3), 1665–1693. https://doi.org/10.5194/hess-22-1665-2018

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., … Sorlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223): 1259855). https://doi.org/10.1126/science.1259855

van Dijk, A. I. J. M., Beck, H. E., Crosbie, R. S., de Jeu, R. A. M., Liu, Y. Y., Podger, G. M., … Viney, N. R. (2013). The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resources Research*, *49*(2), 1040–1057. https://doi.org/10.1002/wrcr.20123

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., … Van Lanen, H. A. J. (2016). Drought in the Anthropocene. *Nature Geoscience*, *9*(2), 89–91. https://doi.org/10.1038/ngeo2646

van Noordwijk, M., & Ellison, D. (2019). Rainfall recycling needs to be considered in defining limits to the world's green water resources. *Proceedings of the National Academy of Sciences*, *116*(17), 8102–8103. https://doi.org/10.1073/pnas.1903554116

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., … Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, *467*(7315), 555–561. https://doi.org/10.1038/nature09440

Wang-Erlandsson, L., Fetzer, I., Keys, P. W., van der Ent, R. J., Savenije, H. H. G., & Gordon, L. J. (2018). Remote land use impacts on river flows through atmospheric teleconnections. *Hydrology and Earth System Sciences*, *22*(8), 4311–4328. https://doi.org/10.5194/hess-22-4311-2018

Watson, J. E. M., Venter, O., Lee, J., Jones, K. R., Robinson, J. G., Possingham, H. P., & Allan, J. R. (2018). Protect the last of the wild. *Nature*, *563*(7729), 27–30. https://doi.org/10.1038/d41586-018-07183-6

Wine, M. L., & Davison, J. H. (2019). Untangling global change impacts on hydrological processes: Resisting climatization. *Hydrological Processes*, *1*, 8. https://doi.org/10.1002/hyp.13483

Wurtsbaugh, W. A., Miller, C., Null, S. E., DeRose, R. J., Wilcock, P., Hahnenberger, M., … Moore, J. (2017). Decline of the world's saline lakes. *Nature Geoscience*, *10*(11), 816–821. https://doi.org/10.1038/ngeo3052

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