A water cycle for the Anthropocene

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Title: A water cycle for the Anthropocene

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Text:

Humor 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 (Wurtsbaugh *et al.*, 2017; Falkenmark *et al.*, 2019; Wine and Davison, 2019). 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 (Attari, 2014; Linton, 2014; Abbott *et al.*, 2019). 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 (Keys *et al.*, 2017; Adler, 2019). 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.

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 and 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 *et al.*, 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 *et al.*, 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 *et al.*, 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 (Fig. 1), which alter both vertical water flow to the atmosphere and lateral movement across, above, and underneath land and water surfaces (DeAngelis *et al.*, 2010; Durack *et al.*, 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 (Linton and Budds, 2014; Van Loon *et al.*, 2016; Falkenmark *et al.*, 2019). 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 (Bradshaw *et al.*, 2007; van Dijk *et al.*, 2013; Paul *et al.*, 2016; Abbott *et al.*, 2019). Second, while 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 our 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 *et al.*, 2019) rather than the primary sources of freshwater for agriculture and ecosystems (Ellison *et al.*, 2012; Heistermann, 2017; Noordwijk and Ellison, 2019).

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 kilometers 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 (Fig. 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 gray (water used to dilute human pollutants), which together exceed global groundwater recharge (Döll and Fiedler, 2008; Gleeson *et al.*, 2016) or the equivalent of half of all the water running from land to sea—24,400 km^3 each year (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 over-allocated, and water pollution (gray water use) causes rampant human disease and ecosystem degradation (Landrigan *et al.*, 2017; Dupas *et al.*, 2019; Falkenmark *et al.*, 2019). 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 runoff 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 U.S. 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 (Keys *et al.*, 2012; Wang-Erlandsson *et al.*, 2018; Gebrehiwot *et al.*, 2019). 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 (Famiglietti, 2014; Huang *et al.*, 2016; Abbott *et al.*, 2019; Falkenmark *et al.*, 2019).

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 (Vörösmarty *et al.*, 2010; Mekonnen and Hoekstra, 2016), 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 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.

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 geographical: 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 (Prudhomme *et al.*, 2014; Abbott *et al.*, 2018; Dottori *et al.*, 2018). Many of the most important water pools and fluxes to 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;

Heistermann, 2017; Falkenmark *et al.*, 2019). 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 vapor from upwind airsheds (Keys *et al.*, 2012). Nearly all the diagrams we analyzed 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; Noordwijk and Ellison, 2019). These engineering "*solutions*" are not only costly and ineffective, they 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 (Linton and Budds, 2014; Abbott *et al.*, 2019; Falkenmark *et al.*, 2019).

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 overrepresent 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.

Global hydrology for global problems

For historical, aesthetic, and disciplinary reasons (Linton and Budds, 2014; Duffy, 2017; Fandel *et al.*, 2018), 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 cycle, 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 (Gunckel *et al.*, 2012; Fandel *et al.*, 2018).

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 and Budds, 2014). While 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.

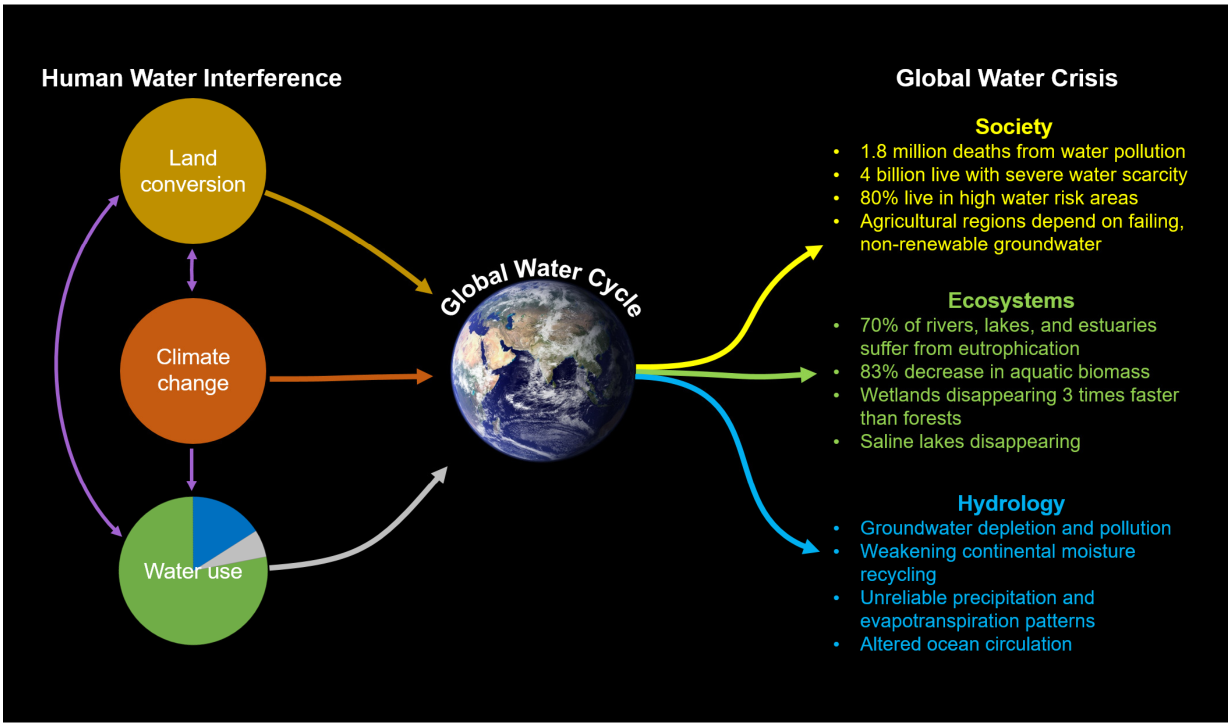

Fig. 1. Types of human interference with the global water cycle and dimensions of the global water crisis. Human water use is separated into green (78%), blue (16%), and gray water use (6%) based on a meta-analysis of global water pools and fluxes (Abbott *et al.*, 2019).


A
B
C
D
E
F
G
H

Fig. 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; F) Flooding of 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.

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