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INNOVATIVE VIEWPOINT

Implicit assumptions of conceptual diagrams in environmental science and best practices for their illustration

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Abstract. In the earth and environmental sciences, many fundamental processes are explained through conceptual illustrations—a powerful medium for scientific communication. The processes depicted are generally highly complex, spatially and temporally variable, subject to high degrees of uncertainty, and non-linearly impacted by anthropogenic actions. Conceptual illustrations necessarily simplify these processes, but also often suffer from a preventable lack of visual clarity, and/or are based on implicit assumptions that are mismatched to key conclusions in published literature. In this Innovative Viewpoint paper, we highlight considerations of conceptual and visual clarity relevant to illustrations in earth and environmental sciences. Using the water cycle as an example, we examine a range of conceptual illustrations of this process to assess what ideas they convey. An exploratory survey of 32 water cycle diagrams shows that they tend to depict generalized, well-defined processes. Anthropogenic influences are included and/or implied in only half the diagrams, and none depict uncertainty in any form. The concept of the water cycle conveyed by these diagrams is therefore not quite the same as the concept of the water cycle as understood by hydrologists. This mismatch may negatively impact decision-making related to water resources management, because the parties involved may unknowingly hold significantly different conceptual models of the processes at work. Other concepts in the earth and environmental sciences may be susceptible to similar issues. Our analysis highlights the importance of carefully assessing the assumptions and simplifying choices inherent in the process of translating a concept into an illustration. We conclude with an example of how these issues can be remedied by presenting a modified water cycle diagram designed to address common misconceptions associated with dryland systems, account for uncertainty in fluxes, and include key anthropogenic effects. A general list of best practices, many of which were used to develop this diagram, is included to help increase awareness among environmental researchers of strategies for increasing the conceptual and visual clarity of illustrations.

Key words: anthropogenic impacts; science communication; science education; scientific illustration; uncertainty; water budget; water cycle.

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Introduction

Environmental scientists face significant challenges in communicating research findings to outside audiences and in prompting desired societal behavior change (Olson 2009, Baron 2010, Moser 2014, 2016). Societal behavior changes are necessary if sweeping global environmental changes are to be counteracted (Perring et al. 2015). These environmental concerns include warming (IPCC 2014), land use conversion (NCA 2014), desertification (MEA 2005), and forest die-off (Allen et al. 2015). Publishing research findings, despite being a key priority in academia, is rarely a successful means of public outreach or of educating future scientists, and seldom results in behavior changes (Mckenzie-Mohr 2000, Callison 2014). More effective forms of communication are therefore needed.

One potentially effective and increasingly common approach to communicating scientific concepts to the public is through visual media, such as scientific illustration—an art form with the explicit purpose of communicating ideas and information. Almost all modern science textbooks rely heavily on illustrations to explain difficult concepts (Bowen and Roth 2002). Similarly, journal articles introducing new ideas commonly use conceptual figures to do so, and these are often the reader's primary means of retaining the information. In fact, papers with a higher number of illustrative diagrams tend to be cited significantly more often (Lee 2017). The illustrations, or "information-dense objects" (Lee 2017), are crucial in shaping and improving readers' understanding of a concept (Mandl and Levin 1989, Carney and Levin 2002). Additionally, it is likely that the process of creating a figure helps researchers solidify their own understanding of the concepts they are trying to communicate—creating images has been shown to help with comprehension and retention of concepts (Cohen and Johnson 2012). In a research group, the process of creating a figure together may have the added benefit of getting all participants on the same conceptual page, especially in interdisciplinary research where all participants may not share the same knowledge base.

Scientific illustration has a long history, ranging from fanciful early representations of "natural curiosities" (Seba 2011, originally published 1734), to painstakingly accurate botanical illustrations and field guides (Hooke 1665), to conceptual diagrams describing processes and system relationships (von Humboldt et al. 1814). Modern scientific illustration has evolved to incorporate certain best practices to ensure accuracy and avoid misleading the viewer, most of which have been codified into the Guild of Natural Science Illustrators' *Guild Handbook of Scientific Illustration* (2003) and into Edward Tufte's *The Visual Display of Quantitative Information* (2001). The effectiveness of these practices has been only partially quantified (Butcher 2006, Sanchez and Wiley 2006, Ali and Peebles 2013). However, the effectiveness of illustrations in general in improving readers' comprehension and retention of information has been well demonstrated (Dwyer 1970). Students are significantly more likely to recall conceptual information after reading a text accompanied by illustrations (Dwyer 1970, Mayer and Gallini 1990, Reinwein and Huberdeau 1997). The impact of poor-quality illustrations is noticeable—when an illustration is ambiguous or not clearly linked to the corresponding text, students develop misconceptions (Benson 1997). It is therefore crucial that the story told by the illustration be an accurate depiction of the current state of understanding of that concept.

Objectives

Although environmental scientists recognize both the need for more effective communication and the potential for scientific illustration as a means of achieving that goal (*public communications*, http://blogs.nature.com/soapboxscience/2013/02/27/why-we-need-science-communication), assessment of how illustrations are actually being used to communicate concepts is largely lacking. In this Innovative Viewpoint paper, we highlight considerations of conceptual and visual clarity relevant to illustrations in earth and environmental sciences. Using the water cycle as an example, we examine a range of conceptual illustrations of this process to assess what ideas they convey. We then present a modified illustration of a dryland water cycle, designed to emphasize certain key concepts from the hydrology literature: the difference between dryland systems and the global water cycle, the uncertainty associated with flux estimates, and the importance of anthropogenic effects. We conclude with a general compilation of best practices that may help increase the conceptual and visual clarity of illustrations in environmental science.

Water Cycle Illustrations as a Case Study

Background

Early illustrations of the water cycle by Athanasius Kircher, from the 17th century, already suggest the basic layout common to most modern water cycle diagrams: a generalized landscape depicting streams originating in the mountains and flowing down to the sea (Fig. 1a). These illustrations are clearly conceptual diagrams, explaining large-scale processes rather than depicting a specific physical location. Certain processes, however, were not yet understood. The origin of springs and streams was explained by several conflicting theories, including seawater filtration, underground condensation, inexhaustible primal reservoirs, and rainfall percolation (the mechanism accepted today; Brutsaert 2005). Kircher's figures depict the underground condensation theory, in which seawater was thought to return to the mountains through underground passageways, where it was geothermally heated before rising as steam and eventually re-emerging through springs (Fig. 1b).

Today, water cycle diagrams generally consist of a similar composite landscape, overlain by arrows and text indicating the major reservoirs and fluxes of water (Fig. 2). Frequently depicted reservoirs include aquifers, oceans, and the atmosphere, while fluxes include evaporation, precipitation, runoff, and recharge. Some diagrams also depict anthropogenic influences such as municipal, industrial, and agricultural water use, dams, or climate change. Finally, the scale of representation ranges from the global water cycle to the routing of water through a single watershed, with the latter diagrams often detailing local, biome-specific processes.

The water cycle was chosen for study because it is broadly referenced as a foundational concept across many environmental disciplines, therefore appearing in a wide range of publication spaces targeted to a variety of different audiences, and yet it is also often misinterpreted (Phillips 1991, Cardak 2009, Romine et al. 2015). Using the water cycle as a case study, we first describe our approach in selecting illustrations to consider and explain our analysis based on classifying the features of each illustration. We then quantify the frequency with which typical features of these illustrations appear, and assess the fit between the concepts conveyed through the illustrations and the concepts prevalent in the current hydrology literature. Finally, we discuss the implications and potential applications of this study.

The water cycle is defined by the United States Geological Survey (Langbein and Iseri 1995) as "a convenient term to denote the circulation of water from the sea, through the atmosphere, to the land; and thence, with many delays, back to the sea by overland and subterranean routes, and in part by way of the atmosphere; also the many short circuits of the water that is returned to the atmosphere without reaching the sea." However, illustrations depicting these processes are captioned with various other terms: "the water cycle," "the water budget," "the hydrologic cycle," "the hydrologic balance." These are sometimes used interchangeably and sometimes not.

The budget or balance (as opposed to the water cycle) for a watershed is commonly defined as the inputs minus the outputs being equal to the change in storage (Healy et al. 2007, Dingman 2015), or as "an accounting of the inflow to, outflow from, and storage in, a hydrologic unit" (Langbein and Iseri 1995). However, a water budget can be (and often is) calculated for the global hydrologic unit, so the distinction between "cycle" and "budget" is not a question of scale alone.

For the purposes of this paper, we use the following definitions, regardless of an image's original caption wording (Fig. 3):

1. global water cycle: a depiction of the general types of water reservoirs and fluxes found on Earth, intended to represent the entire global system, with no external inputs or outputs of water.
2. global water budget: quantitative estimates of the global magnitudes of each type of water reservoirs and fluxes.
3. local water cycle: a depiction of the specific water reservoirs and fluxes found at the region, biome, or watershed scale, which have external inputs or outputs of water.
4. local water budget: quantitative estimates of the magnitudes of each water reservoir and flux found in a biome, region, or watershed.

For all of these subcategories, basic definitions and diagrams do not always reflect the complexity of an actual water cycle or water budget. The

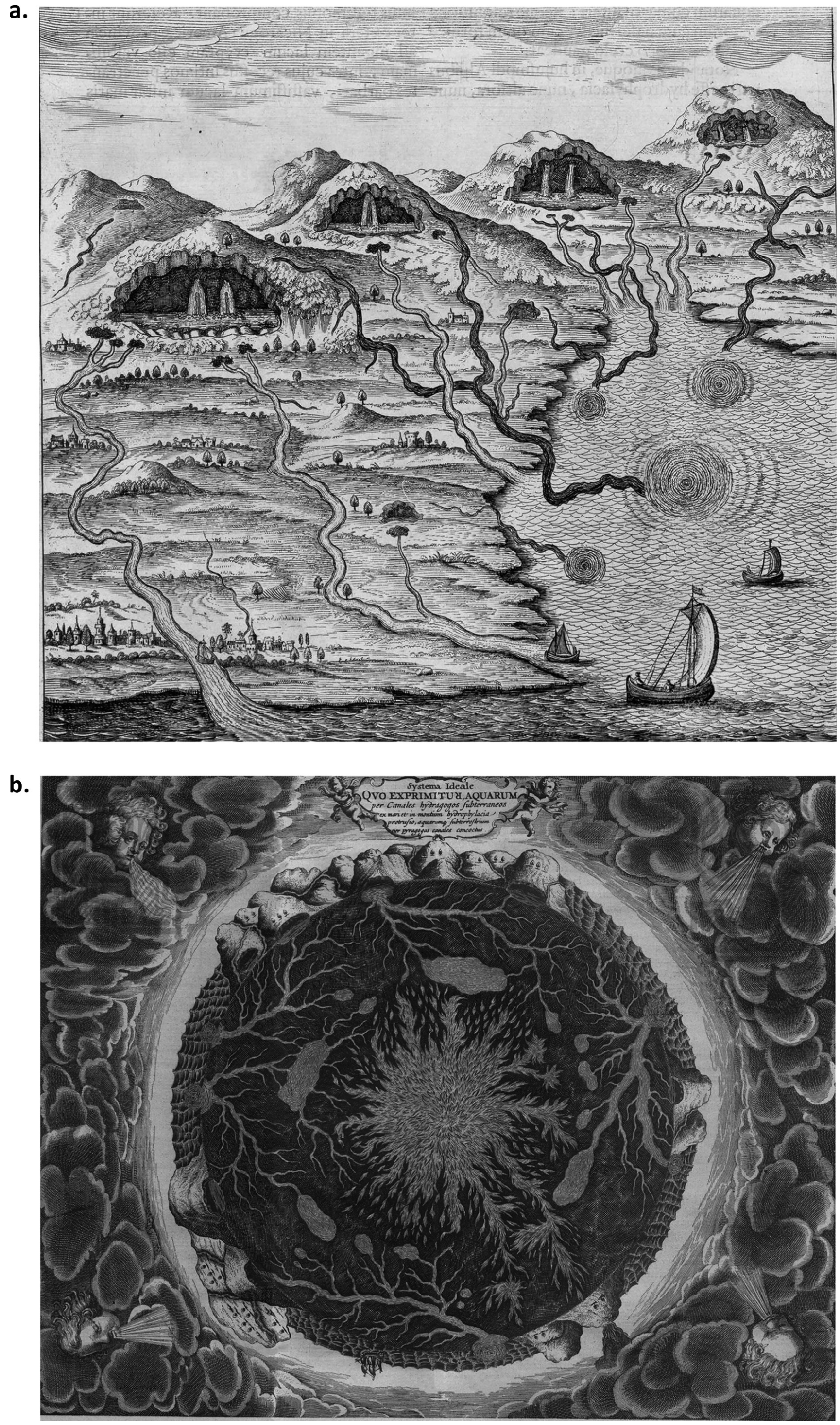


Fig. 1. Early depictions of the water cycle (17th century). (a) Generalized landscape similar in layout to modern water cycle diagrams. (b) Kircher's proposed mechanism for the circulation of water—seawater flows through whirlpools into the ground, where it is heated into steam and rises back into the mountains, to then re-emerge from springs. Source: Kircher (1665).

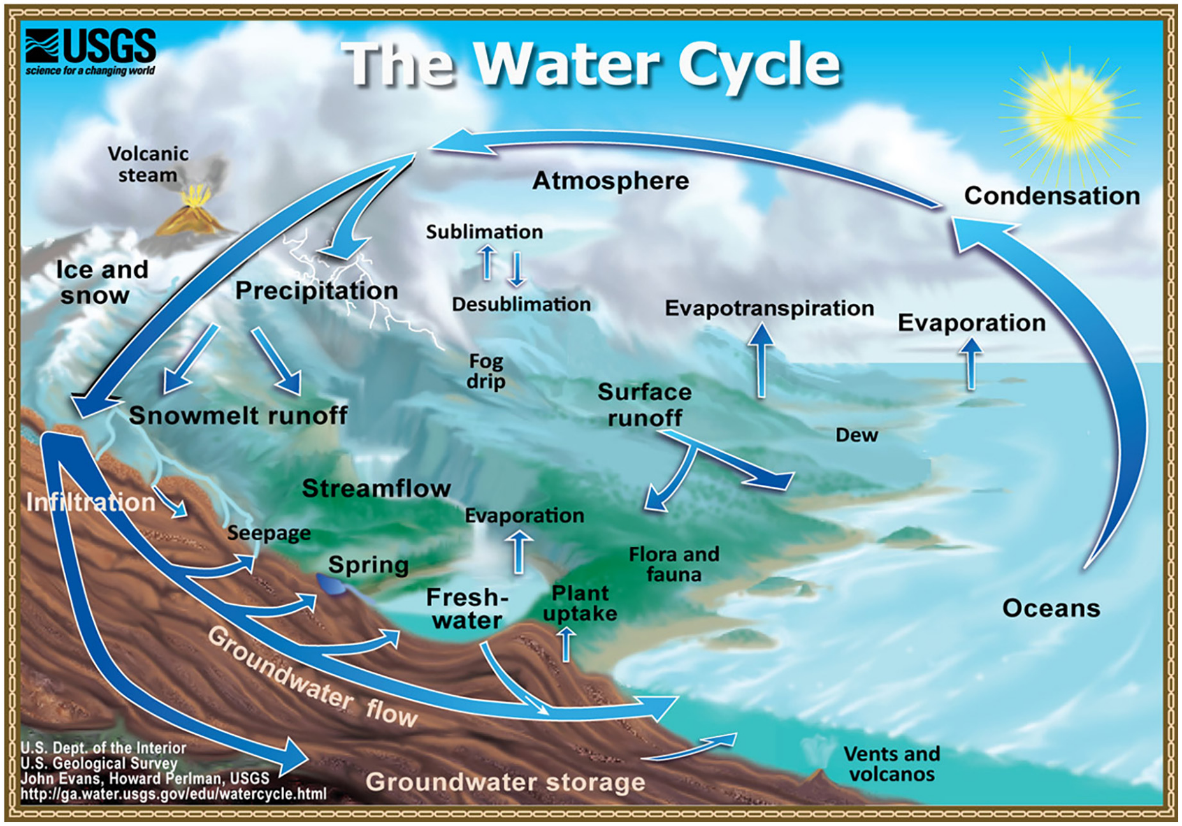


Fig. 2. A typical representation of the global water cycle, from the United States Geological Survey. This is the first image returned by a Google keyword search for "water cycle." Note the presence of flux arrows but not quantitative estimates, and the absence of anthropogenic impacts. Source: *Public communications*, https://water.usgs.gov/edu/watercycle.html. U.S. Geological Survey, Department of the Interior. Illustration by J. Evans and H. Perlman.

reservoirs and fluxes involved are difficult to quantify, highly spatially and temporally variable, and non-stationary (Milly et al. 2008). Despite the well-established importance of reporting uncertainty, and the increasing recognition that anthropogenic influences are amplifying the long-term range of variability of hydrologic fluxes, these fluxes are still often reported only as a single mean value.

It has been argued that the discrepancy between the apparently simple definition and the complex reality leads to misperceptions. For example, Alley (2007), Bredehoeft (2002), and Devlin and Sophocleous (2005) all highlight misunderstandings surrounding estimates of the quantity of water available from aquifers for human use. Other misconceptions about the movement of water through the landscape are also widespread, possibly arising from overly simplified visual depictions of the water cycle. At the global scale, these misconceptions include the following:

1. Aquifers are underground lakes or rivers (Phillips 1991, Covitt et al. 2009).
2. Groundwater is not connected to surface water (Cardak 2009).
3. The amount of water in the atmosphere is constant (Cardak 2009).
4. Pollutants can travel both upstream and downstream from the source (Covitt et al. 2009).
5. Evaporation only occurs from oceans (Bar 1989, Henriques 2002).
6. Humans are not connected to the water cycle (Cardak 2009).

Interestingly, one study found that students from urban areas made significantly fewer

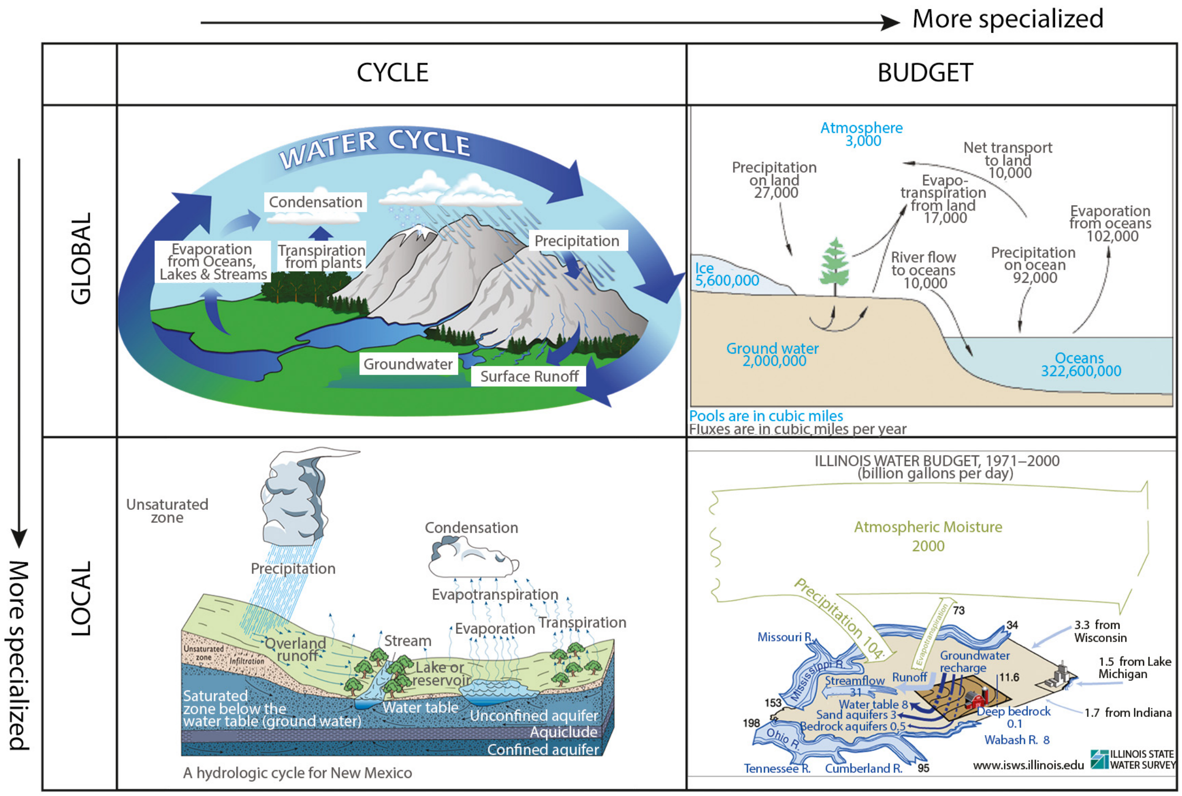


Fig. 3. Representative water cycle diagrams in each of four categories: (a) the global water cycle: a depiction of the general types of water reservoirs and fluxes found on Earth, intended to represent the entire global system, with no external inputs or outputs of water. (b) The global water budget: quantitative estimates of the global magnitudes of each type of water reservoirs and fluxes. (c) The local water cycle: a depiction of the specific water reservoirs and fluxes found at the region or watershed scale, which may have external inputs and outputs of water. (d) The local water budget: quantitative estimates of the magnitudes of each water reservoir and flux found in a region or watershed. Sources: (a) *Public communications,* https://pmm.nasa.gov/education/water-cycle. Used with permission from NASA. (b) Winter et al. (1998). Used with permission from the U.S. Geological Survey. (c) Johnson et al. (2003). Used with permission from the New Mexico Bureau of Geology and Mineral Resources. (d) *Public communications,* http://www.isws.illinois.edu/docs/watercycle/. Used with permission from the Illinois State Water Survey.

connections between human water use and the water cycle than students from rural areas (Ben-Zvi Assaraf et al. 2012). For dryland systems specifically, little research is available, but we have identified three common misconceptions based on informal observations and feedback from teachers and from K-12, undergraduate, and graduate students in Tucson, Arizona (C. A. Fandel, *personal observation*).

1. A diagram labeled with flux and reservoir volume estimates may prompt the conclusion that these values remain constant year to year and that scientists know exactly how much water is going where.
2. The mismatch between the day-to-day precipitation and vegetation patterns that students experience and those depicted in a global diagram may lead to confusion and distrust.
3. Neatly diagrammed and labeled illustrations may give the impression that hydrologists understand the water cycle perfectly and that no further research is needed.

These types of misperception may make it difficult for scientists and managers to approach water resources problems collaboratively and creatively, because each person may unknowingly hold a different internal conceptual model of the same physical system.

Approach

To find illustrations for analysis, we employed two different approaches. First, in order to assess the range of illustrations available, we used Google Image Search to sample the first 60 results returned for each of the following search terms: "water cycle," "hydrologic cycle," "water budget," and "hydrologic budget." This yielded 240 images, which we then classified into the four broad categories defined above (global water cycle, global water budget, local water cycle, and local water budget). Second, we assembled a subset of images for more detailed analysis. These included an even smaller subset of biome-specific images—we chose to particularly focus on dryland systems, which are both visually and functionally dissimilar from global diagrams. We searched through publications from multiple disciplines, including hydrology, geology, resource management, forestry, environmental science, soil science, and climate and atmospheric science, as well as general reference texts. Approximately half of the illustrations were found through Google Image Search, with the following keywords: "water cycle," "hydrologic cycle," "water budget," "hydrologic budget," "arid water cycle," "arid hydrologic cycle," "arid water budget," and "arid hydrologic budget." The remaining illustrations were found by surveying the textbooks available in the University of Arizona Department of Hydrology and Atmospheric Sciences Library and in the University of Arizona Sciences Library's Geology, Hydrology, and Environmental Sciences sections. From these sources, we selected illustrations published between 1985 and 2016, including images targeted to a range of audiences: K-12 education materials, introductory college-level textbooks, graduate-level textbooks, and government reports and websites for the general public. This approach yielded a combined representative (but not exhaustive) set of 32 examples of water cycle and water budget diagrams (Table 1 for summary and Appendix S1 for image sources). These examples were selected regardless of scale (global vs. local) or type (cycle vs. budget).

For this subset of 32 images, we classified each illustration into a category based on the definitions above, regardless of the wording used in the original caption. We also assigned the diagrams to categories based on their intended audience, their publication medium, and the disciplinary background of the publication. We then compiled a list of elements, such as "solar energy input," "agricultural water use," and "flux arrows," that appeared in at least one of the diagrams. We noted the presence or absence of each of these elements, as well as whether uncertainty margins on quantitative flux estimates were shown, and whether the landscape depicted was humid or arid, for each illustration (Appendix S2).

Analysis and results

In our Google Image Search, we found that out of the 240 surveyed search results, 47.5% depicted the global water cycle, 4.2% depicted the global water budget, 17.9% depicted a local water cycle, 5.4% depicted a local water budget, and 25% did not depict the water cycle or a water budget. In the more thoroughly studied 32 images from a diversity of sources, we found that reservoirs and many types of fluxes were commonly depicted, but that biome-specific features, anthropogenic impacts, and uncertainty were less common. Most diagrams depicted the global water cycle and featured a lush green landscape. Very few examples of arid biome-specific diagrams were found, despite targeted searching. Humid systems dominated the sample of illustrations—only five of the 32 diagrams showed dryland-specific processes. While understanding the global water cycle is useful and necessary, it is not sufficient when attempting to make sense of arid systems. Additionally, none of the diagrams depicted uncertainty in flux amounts or in any other form (Fig. 4a). Finally, despite the increasingly large role that anthropogenic activities play in the water cycle, only 50% of the 32 surveyed diagrams included any form of anthropogenic impacts (Fig. 4a). However, the proportion of those that did increased from ~10% for illustrations published between 1985 and 2000 to 68% for those published between 2001 and 2016 (Fig. 4b). The increasing frequency with which anthropogenic impacts are included suggests that illustrators and/or authors are becoming aware of their importance and/or are increasingly choosing to emphasize them.

Table 1. Sources for illustrations surveyed in this study.

Author	Year	Publisher	Discipline	Intended audience
Hamblin	1986	Prentice Hall	Geology	University
FAO	1989	FAO/UN	Forestry	Managers
Stute	2002	Lamont-Doherty Observatory	Hydrology	General public
Debari	2004	Western Washington University	Geology	University
NSW Office of Environment and Heritage	2013	NSW OEH	Hydrology	General public
Encyclopedia Britannica	2014	Encyclopedia Britannica	General	General public
NASA	2016	NASA	Atmospheric Science	K-12
Bice	2016	Pennsylvania State University	Geology	University
Evans and Perlman	2016	USGS	Hydrology	General public
Hughes	2016	Idaho State University	Geology	University
UK Met Office	2016	UK Met Office	Atmospheric Science	K-12
Berner and Berner	1987	Prentice Hall	Hydrology	University
Henry and Heinke	1989	Prentice Hall	Environmental Science	University
Maidment	1993	McGraw-Hill	Hydrology	University
Maidment	1993	McGraw-Hill	Hydrology	University
Tarbuck and Lutgens	1993	MacMillan	Geology	University
Winter et al.	1998	USGS	Hydrology	University
Montgomery	2013	McGraw-Hill	Geology	University
Dingman	2015	Waveland Press	Hydrology	University
Hendricks et al.	1985	University of Arizona	Soil Science	University
Boers	1994	International Institute for Land Reclamation and Improvement	Management	General public
KS Geological Survey	2005	KS Geological Survey	Geology	General public
KS Geological Survey	2005	KS Geological Survey	Geology	General public
NCA	2009	Cambridge University Press	Climate	General public
Tucson Water	2012	Tucson Water	Management	General public
Tucson Water	2014	City of Tucson	Management	General public
IL State Water Survey	2016	University of Illinois	Hydrology	General public
NM Bureau of Geology and Mineral Resources	2016	University of New Mexico	Geology	Managers
Murray-Darling Basin Authority	2016	Commonwealth of Australia	Hydrology	General public
Dingman	2015	Waveland Press	Hydrology	University
USGS	2014	USGS	Hydrology	General public
IL State Water Survey	2016	University of Illinois	Hydrology	General public

Notes: Illustrations were chosen to represent a range of disciplines, publication venues, and intended purposes. Sources: Public Communications: Stute, 2002, http://www.ldeo.columbia.edu/~martins/pfaz/story_line.html; Debari, 2004, http://faculty.wwu.edu/~debari/web/g101/lec15.html; NSW Office of Envt. & Heritage, 2013, http://www.environment.nsw.gov.au/salinity/basics/water.htm; Encyclopedia Britannica, 2014, https://www.britannica.com/science/water-cycle; NASA, 2016, https://pmm.nasa.gov/education/water-cycle; Bice, 2016, http://www3.geosc.psu.edu/~dmb53/DaveSTELLA/Water/global%20water/global_water.htm#intro; Evans and Perlman, 2016, http://water.usgs.gov/edu/watercycle.html; Hughes, 2016, http://geology.isu.edu/wapi/EnvGeo/EG7_water/EG_module_7pt1.htm; UK Met Office, 2016, http://www.metoffice.gov.uk/learning/weather-for-kids/water-cycle; Tucson Water, 2012, http://www.slideshare.net/CWAA/spotlight-tucson-pima-county-arizona; Tucson Water, 2014, https://www.tucsonaz.gov/water/cycle; IL State Water Survey, 2016, http://www.isws.illinois.edu/docs/watercycle/; Murray-Darling Basin Authority, 2016, https://www.mdba.gov.au/discover-basin/water/discover-surface-water; USGS, 2014, http://water.usgs.gov/watercensus/water-budgets.html; IL State Water Survey, 2016, http://www.isws.illinois.edu/docs/watercycle/

Other factors, such as the intended audience of the illustration, the type of publication it appears in, and the discipline it targets, also appear related to whether anthropogenic influences are shown (Appendix S2). For example, illustrations published on agency websites depicted human impacts more frequently than those published in textbooks, reports, course webpages, or other venues. Similarly, human impacts were more frequently depicted in illustrations targeted to the general public than in those targeted to academics, managers, or K-12 students. The target discipline appeared to have less of an influence on whether anthropogenic impacts were included,

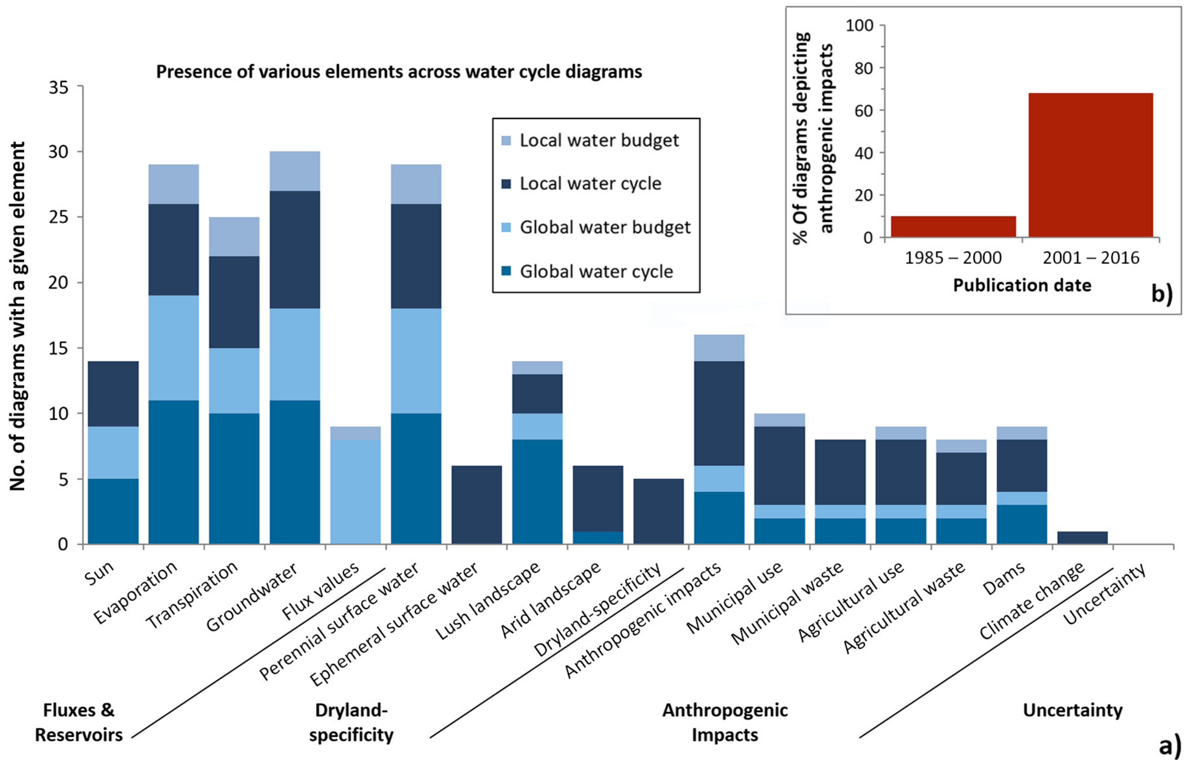


Fig. 4. Frequency of appearance of various different elements in a sample of 32 water cycle illustrations. Elements include basic fluxes and reservoirs, anthropogenic impacts, biome specificity, and uncertainty. Only half of the sampled illustrations depicted anthropogenic impacts, but the bulk of those that did were published more recently (see inset b). This suggests that depictions of anthropogenic impacts are more common in newer illustrations. None of the sampled illustrations depicted any form of uncertainty.

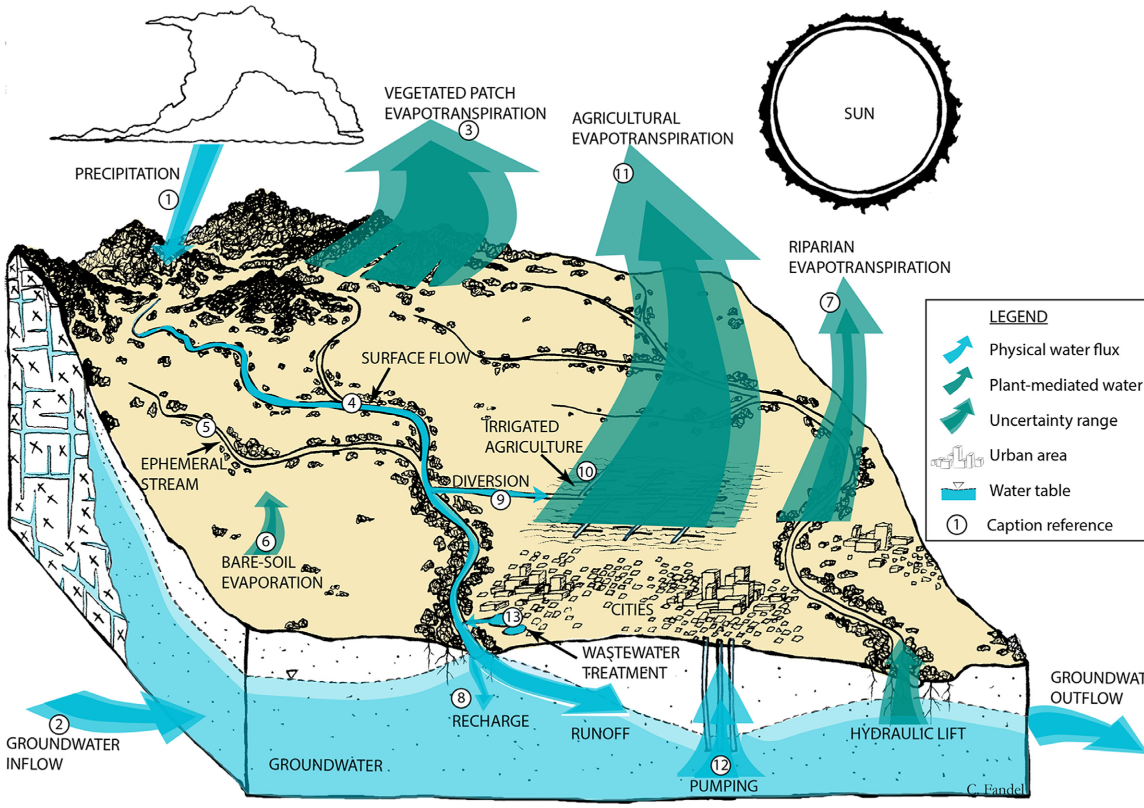
though interestingly, the only category where all of the illustrations were devoid of human presence was "Environmental Science, Soil Science, and Forestry." Lastly, although anthropogenic impacts such as direct water use or dam construction appeared in many illustrations, only one diagram referenced climate change: the 2009 National Climate Assessment's summary figure of climate impacts on the water cycle in the United States.

As noted above, the lack of depiction of uncertainty is particularly striking given that water flux estimates are known to be highly uncertain (Sivapalan et al. 2003, Liu and Gupta 2007). The diagrams that included quantitative flux estimates implied a certain degree of uncertainty through the number of significant figures included, but we could find no explicit mention of it in the captions and no visual representations in the diagrams themselves.

An alternative depiction of a dryland water cycle inclusive of uncertainty

This case study aimed to assess the fit between conceptions of the water cycle in the hydrology literature and depictions of the water cycle in a representative selection of conceptual illustrations. Analysis of these illustrations reveals a mismatch: The literature highlights the importance of understanding and quantifying uncertainty, the high spatial and temporal variability of hydrologic systems, and the increasingly significant changes resulting from human activities. The illustrations, however, do not include uncertainty at all, are mostly broadly generalized to smooth out local variability, and only depict the presence of humans 50% of the time.

Illustrations that more closely match the literature are not necessarily more challenging to create.



This diagram shows how water moves through an arid watershed. The arrows indicate the major water fluxes, with the size ranges showing the uncertainty in measurement – some water movements are difficult to quantify. These fluxes also vary from year to year and from location to location, and may even be going through long-term changes due to human influences such as climate change, though this is not shown here. The green arrows show vegetation-mediated fluxes, which play an important role in the water cycle. Water flows into the watershed through precipitation ①, which is usually minimal, and through lateral ground -water movement ②. Precipitation falling on vegetated patches is mostly returned to the atmosphere as evapotranspiration ③, and partly routed as runoff into perennial ④ and ephemeral ⑤ stream channels. Precipitation that falls onto bare ground partly flows into surface streams, and partly is directly evaporated ⑥. As the water flows through streams, some is taken up and transpired by riparian vegetation ⑦, some is evaporated directly from the stream surface, some infiltrates through the channel floor and eventually recharges local groundwater reserves ⑧, and some is diverted ⑨ for human agricultural, industrial, or municipal use. Natural recharge in arid systems occurs almost exclusively through stream channels. Artificial recharge can also occur beneath irrigated agricultural areas ⑩, although a large portion of the irrigation water is returned to the atmosphere through evapotranspiration ⑪. Water for human use often comes from a combination of captured surface water and pumped groundwater. The rate of pumping in arid systems is often much higher than the rate of recharge, creating cones of depression near wellfields as groundwater reserves are depleted ⑫. After use, human wastewater ⑬ is then often treated and returned to the stream system or recharged in artificial basins to mitigate the effects of pumping.

Fig. 5. Prototype of a water cycle diagram and accompanying descriptive text for an arid region. This figure (a) explicitly depicts uncertainty with varying arrow sizes, (b) explicitly depicts anthropogenic impacts such as municipal and agricultural water uses, (c) is biome-specific for drylands, showing the relative importance of ET and depicting minimal vegetation outside of riparian areas and mountaintops. The text is based on the published literature, including but not limited to the following sources: D'Odorico et al. (2010), Newman et al. (2010), Seyfried et al. (2005), Wilcox et al. (2003), and Wilcox (2017).

Fig. 5 is a prototype of such an illustration, closely grounded in the literature, for an arid region. We chose to emphasize the following elements:

1. Explicit depictions of uncertainty.
2. Explicit depictions of anthropogenic impacts.
3. Biome-specific depictions of dryland hydrologic processes.

These choices necessarily eliminate or de-emphasize elements that specialists from other disciplines would have included.

Table 2. A sample of best practices for conceptual illustrations.

No.	Best practices	Example references
1	Consider the value of developing a figure specific to the audience and concept of interest, based on key findings from the literature, rather than beginning with modification of an existing figure.	Rougier et al. (2014), Garland guidelines‡, Dwyer (1970)
2	Do not include decorative images: Adding irrelevant images to text decreases learning.	Sanchez and Wiley (2006)†
3	Obtain feedback from the target audience to identify possible misinterpretations.	Benson (1997)†
4	Include cues in the main text to guide the reader in knowing when and how to look at the figure.	Coleman and Dantzler (2016)†
5	Use high contrast (between tones or colors) to draw attention to key elements.	Shang and Bishop (2000)†, O'Connor (2015)†
6	Use consistent visual cues (color, texture, size, shape) to indicate conceptually related objects: Viewers tend to conceptually group objects with similar visual characteristics.	Ali and Peebles (2013)†
7	Include a clearly labeled key and scale.	Benson (1997)†, Ridgway (1920)
8	To convey change over time, use a series or step-by-step images. Also, consider using an animation instead of an illustration (animations are sometimes more effective).	Fukuoka et al. (1999)†, Türkay (2016)†
9	Minimize the visual elements that are not central to the main concept of the illustration: A simple line drawing is more effective than a realistic drawing or a photograph.	Reinwein and Huberdeau (1997)†, Butcher (2006)†, Rougier et al. (2014)
10	Use color: Color increases comprehension in university-level students. Choose colors that reproduce well and are distinguishable to colorblind people.	Reinwein and Huberdeau (1997)†, Dwyer (1970)†, Okabe and Ito§
11	Limit the number of concepts per figure. Use visual subdivisions such as grouping, multiple panels, and zooms for concepts that are too complex to be explained in a single panel.	Rougier et al. (2014)
12	Use parallel structure (e.g., if the *x*-axis is the same for three panels, they should be aligned horizontally; only change the component of the figure that is the focus of the change being highlighted).	Tufte (2001)
13	Use a consistent, simple font with minimal acronyms or abbreviations.	NMNH¶, Garland guidelines‡, Ridgway (1920)
14	Use a professional medium: graphics software such as Adobe Illustrator, Inkscape, or GIMP rather than PowerPoint; or pen and ink rather than pencil.	Tufte (2001), Hodges (2003), Ridgway (1920)
15	Draft the figure at roughly 2× the scale of the final print version to ensure that it will reproduce clearly.	Hodges 2003
16	Develop illustration skills by using tutorials	See Appendix S3

Notes: Not all practices necessarily apply to all cases. References marked with a cross (†) indicate studies demonstrating the effectiveness of the corresponding practice.
‡ *Public communications*, http://www.garlandscience.com/res/pdf/GS_Illustration_Guidelines.pdf
§ *Public communications*, http://jfly.iam.u-tokyo.ac.jp/color/
¶ *Public communications*, https://paleobiology.si.edu/paleoArt/Techniques/pages/tech1.htm

The figure caption includes a sample of text that would accompany the figure if it were presented in a college-level textbook. The caption also makes note of characteristics not depicted in the illustration, such as spatial and temporal variability. Variability could be further explained by an accompanying figure, such as graph of average precipitation in several different watersheds over ten years, though we did not choose to include this here.

This type of illustration, informed by the literature, is not drastically different from existing diagrams, and is intended to supplement, not replace them. It is intended as an example of the importance of making conscious decisions, grounded in the literature, with respect to which elements to include, rather than simply re-using a pre-existing figure that may implicitly convey unintended messages. This new figure may have the potential to shift public perceptions and student understanding of the difference between the global water cycle and the local water fluxes in arid regions.

Some Best Practices for Improving Conceptual Illustration in Earth and Environmental Sciences

The water cycle is not the only concept subject to the issues we identified in our case study. Other systems with well-established visual representations include food webs, carbon and nitrogen cycling, and ecological adaptation, all often explained through diagrams in textbooks, and all

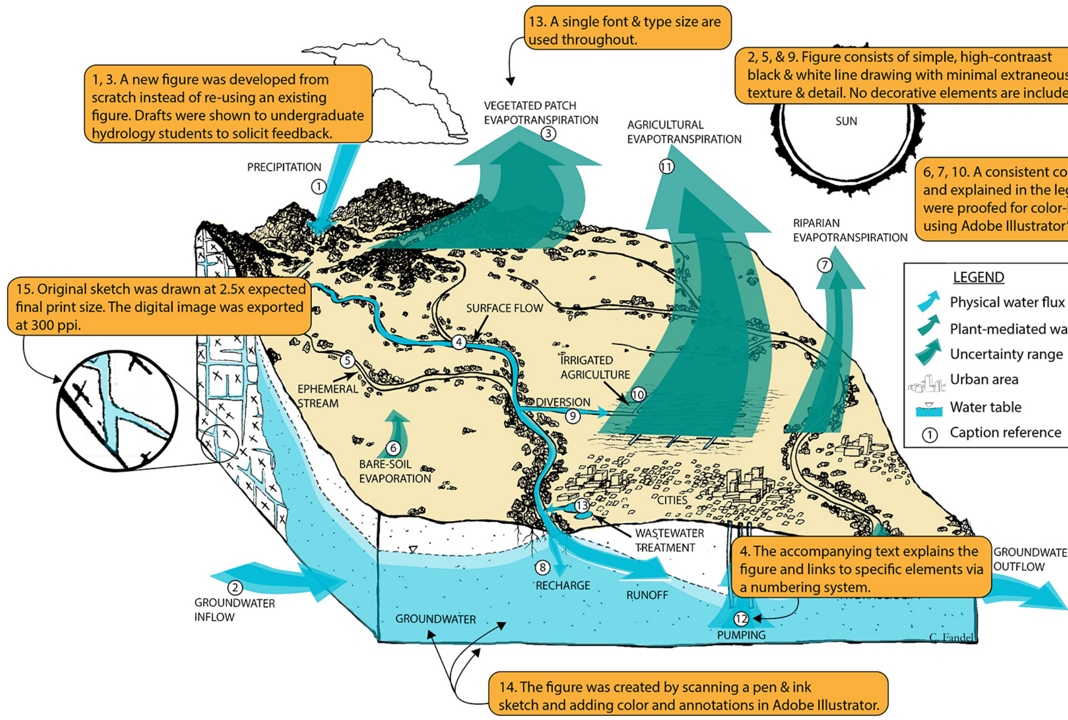


Fig. 6. Annotation of Fig. 5, highlighting which best practices from Table 2 were used and where.

subject to frequent misinterpretation by students (Munson 1994). These and other concepts might also benefit from an approach to illustration that consciously considers common student misconceptions or changes in the current state of knowledge about these topics. This includes educational libraries such as the Ecological Society of America's EcoEd Digital Library (*public communications*, http://ecoed.esa.org/).

There are numerous resources available for improving scientific illustrations. Here, we present a select list of general best practices for both conceptual and visual clarity that scientists could leverage to improve conceptual diagrams (Table 2). These include research-based strategies for using color effectively, for linking images and their accompanying text, and for laying out an illustration. Not all of these practices need necessarily apply to every figure, but keeping them in mind during the figure design process may be helpful. To demonstrate this, we include an annotated version of Fig. 5, with each best practice used highlighted (Fig. 6). We also include links to online tutorials to develop specific illustration skills. In summary, as the challenges caused by global change become more pressing, effective science communication and outreach are ever more important. Carefully thought out conceptual illustrations are one particularly powerful means of advancing this goal.

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2072/full