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Global Groundwater Sustainability, Resources, and Systems in the Anthropocene

Tom Gleeson,[1] Mark Cuthbert,[2,3] Grant Ferguson,[4] and Debra Perrone[5]

[1]Department of Civil Engineering and School of Earth and Ocean Sciences, University of Victoria, British Columbia V8W 3P5, Canada; email: tgleeson@uvic.ca

[2]School of Earth and Ocean Sciences and Water Research Institute, Cardiff University, Cardiff CF10 3AT, United Kingdom

[3]Connected Waters Initiative Research Centre, University of New South Wales, Sydney, New South Wales 2052, Australia

[4]Department of Civil, Geological and Environmental Engineering, University of Saskatchewan, Saskatoon, Saskatchewan S7N 5E5, Canada

[5]Environmental Studies Program, University of California, Santa Barbara, California 93106-1100, USA

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Abstract

Groundwater is a crucial resource for current and future generations, but it is not being sustainably used in many parts of the world. The objective of this review is to provide a clear portrait of global-scale groundwater sustainability, systems, and resources in the Anthropocene to inspire a pivot toward more sustainable pathways of groundwater use. We examine groundwater from three different but related perspectives of sustainability science, natural resource governance and management, and Earth System science. An Earth System approach highlights the connections between groundwater and the other parts of the system and how these connections are impacting, or are impacted by, groundwater pumping. Groundwater is the largest store of unfrozen freshwater on Earth and is heterogeneously connected to many Earth System processes on different timescales. We propose a definition of groundwater sustainability that has a direct link with observable data, governance, and management as well as the crucial functions and services of groundwater.

- Groundwater is depleted or contaminated in some regions; it is ubiquitously distributed, which, importantly, makes it broadly accessible but also slow and invisible and therefore challenging to govern and manage.
- Regional differences in priorities, hydrology, politics, culture, and economic contexts mean that different governance and management tools are important, but a global perspective can support higher level international policies in an increasingly globalized world that require broader analysis of interconnections and knowledge transfer between regions.
- A coherent, overarching framework of groundwater sustainability is more important for groundwater governance and management than the concepts of safe yield, renewability, depletion, or stress.

> "Earth provides enough to satisfy every human's needs, but not every human's greed."
>
> —Mahatma Gandhi[1]

1. INTRODUCTION

1.1. Motivation

Three important questions introduce and motivate this review: Why are groundwater resources and sustainability important and threatened? How is groundwater connected to various parts of the Earth System? Why is examining groundwater at global scales important?

1.1.1. Why are groundwater resources and sustainability important and threatened?

Groundwater is a critical resource for people, economies, and the environment. Groundwater provides approximately two billion people with drinking water (Morris et al. 2003) and supplies ∼40% of global irrigation (Siebert et al. 2010). Groundwater pumping has facilitated significant social development critical to poverty alleviation and economic growth, enhanced food security, and alleviated risks from drought in many farming regions (Giordano 2009, Giordano & Villholth 2007). It is crucial to a diverse range of groundwater-dependent ecosystems (Kløve et al. 2011) and environmental flows, which are the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems that, in turn, support human cultures, economies, sustainable livelihoods, and well-being (Arthington et al. 2018, Gleeson & Richter 2018). Groundwater could be important to Agenda 2030 of the United Nations and its 17 sustainable development goals (SDGs) (Guppy et al. 2018), which incorporate these multiple roles of water in development as well as the importance of maintaining water functions in the environment (see the sidebar titled Groundwater and the Sustainable Development Goals).

Unfortunately, groundwater resources are threatened globally in many different regions where both quantity and quality issues are common (Aeschbach-Hertig & Gleeson 2012, Bierkens & Wada 2019, Foster & Chilton 2003, Lall et al. 2020, Margat & Van der Gun 2013). The direct impacts of groundwater use can be land subsidence, enhancement of hydrological drought, sea-level rise, groundwater salinization, and impact on groundwater-dependent ecosystems (see Bierkens & Wada 2019, and references therein). These direct impacts can have broader sustainability impacts on water, food, and energy security; infrastructure; social well-being; and local economies. Additionally, there can be broader impacts on Earth Systems such as oceans

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[1] Slightly rephrased from "man" to "human."

GROUNDWATER AND THE SUSTAINABLE DEVELOPMENT GOALS

Groundwater is an important resource for achievement of the UN Sustainable Development Agenda for 2030, yet it is poorly recognized and weakly conceptualized in the sustainable development goals (SDGs) (Guppy et al. 2018). Groundwater could be important to ensuring access to water and sanitation for all (Goal 6) as well as contributing to several other goals: poverty eradication (Goal 1), food security (Goal 2), gender equality (Goal 5), sustainability of cities and human settlement (Goal 11), combating climate change (Goal 13), and protecting terrestrial ecosystems (Goal 15). Yet even in the targets of Goal 6, groundwater is explicitly referenced only once, and a detailed analysis by Guppy et al. (2018) was necessary to highlight the potential relationships between groundwater and many other targets. More than half of these relationships are reinforcing, meaning that achievement of the target would have a positive impact on groundwater. Yet the few conflicting relationships where achievement of the target would have a negative impact on groundwater are important because conflicting relationships are the most critical and difficult ones to manage. The most important potentially conflicting relationship may be between groundwater and some of the targets for food security (Goal 2), including ending hunger and doubling agricultural productivity (Guppy et al. 2018).

(e.g., coastal eutrophication), climate (e.g., groundwater-climate interactions), or lithosphere (e.g., critical zone or petroleum resources); these broader impacts generally have not been as well recognized or described as the direct impacts.

1.1.2. How is groundwater connected to various parts of the Earth System? Groundwater connects various parts of the Earth System as an intermediary between fast processes at or above the surface of Earth and slower processes deeper in Earth. The Earth System comprises different interacting components such as the hydrosphere, lithosphere, atmosphere, and biosphere; note that we follow Steffen et al. (2006) in capitalizing Earth System to emphasize that Earth functions as a single, complex, interacting system. At or above the land surface, groundwater systems can modulate surface energy and water partitioning with a long-term memory (Anyah et al. 2008, Bresciani et al. 2016, Condon & Maxwell 2019, Cuthbert et al. 2019a, Keune et al. 2018, Krakauer et al. 2014, Maxwell & Kollet 2008, Meixner et al. 2016, Taylor et al. 2013) and contribute to streamflow and groundwater-dependent ecosystems (Batelaan et al. 2003, Boulton & Hancock 2006, Kløve et al. 2011). Groundwater also impacts the oceans through influencing both sea level (Döll et al. 2014, Wada 2016) and freshwater and solute inputs to the ocean (Moore 2010, Sawyer et al. 2016, Zektser et al. 2007). It is important in several geological processes (Tóth 1999) including tectonics and faulting (Townend & Zoback 2000); induced seismicity (Keranen & Weingarten 2018); formation of mineral deposits (Garven & Freeze 1984, Raffensperger & Garven 1995); rock-forming and -altering processes, such as dolomitization (Machel & Mountjoy 1986); and migration of hydrocarbons (Hindle 1997, Person et al. 1996). Groundwater flow and chemistry are also related to biological activity in the subsurface and are a control on carbon cycling in the continental crust (Simkus et al. 2016) and microbial generation of methane (Martini et al. 1998). Even though groundwater is clearly important for myriad Earth System processes, a holistic view of groundwater in the Earth System, as we develop below, is rare in both Earth System science and hydrogeology communities. Groundwater may also be important within an Earth System sustainability framework—the planetary boundaries (Rockström et al. 2009, Steffen et al. 2015)—although this has not previously been discussed at length (see the sidebar titled Groundwater and the Planetary Boundaries).

GROUNDWATER AND THE PLANETARY BOUNDARIES

Earth System science, complex system theory, and sustainability science have been combined with the planetary boundary framework, defined as biogeophysical boundaries at the planetary scale for the processes and systems that together regulate the state of the Earth System (Rockström et al. 2009, Steffen et al. 2015). Planetary boundaries have been adopted in sustainability governance and corporate management, but the current planetary boundary for freshwater use has been highly criticized (Heistermann 2017). Recently Gleeson et al. (2020) argued that the current water planetary boundary, which is based on summing global streamflow and water use, should be replaced because it does not adequately represent the role of water in influencing critical Earth System functions. Instead, key functions of water in the Earth System were identified, including hydroclimatic and hydroecologic regulation, and transport and an ambitious roadmap were proposed for identifying new water planetary boundaries for streamflow, groundwater, atmospheric water, soil moisture, and frozen water. The key functions of groundwater in the Earth System were argued to be hydroecologic regulation, especially in relation to terrestrial or aquatic biosphere integrity, and storage in relation to sea-level rise.

1.1.3. Why is examining groundwater at global scales important? Just a decade ago, groundwater was generally ignored in global hydrology models before global groundwater recharge was estimated for the first time (Döll & Fiedler 2008). Seminal groundwater sustainability reviews highlighted that groundwater was critical to agriculture and people and was locally overused or contaminated but also that groundwater recharge, use, and quality were largely unknown for vast parts of the world or at least not synthesized into a cohesive and consistent global perspective (Foster & Chilton 2003, Giordano 2009, Moench 2004, Zektser & Everett 2000). Continental-to global-scale studies of groundwater systems, resources, and sustainability have proliferated in the last decade; this review synthesizes this proliferation with a strong rooting in fundamental hydrogeology, Earth System science, and sustainability science.

Considering groundwater at continental to global scales (Gleeson et al. 2019) allows us to (*a*) understand and quantify the two-way interactions between groundwater and the rest of the hydrologic cycle, as well as the broader Earth System; (*b*) inform water governance and management for large, and often transboundary, groundwater systems (Wada & Heinrich 2013) in an increasingly globalized world with virtual water trade (Dalin et al. 2017); (*c*) consistently and systematically analyze problems and solutions globally regardless of local context, which could enable prioritization of regions or knowledge transfer between regions; and (*d*) create visualizations and interactive opportunities that are consistent across the globe to improve understanding and appreciation of groundwater resources.

It is important to simultaneously view groundwater globally and regionally because groundwater does not operate solely on global scales or regional scales but on both scales at once. Groundwater depletion is considered a global problem owing to its widespread distribution and its potential consequences for water and food security and sea-level rise (Aeschbach-Hertig & Gleeson 2012, Konikow & Kendy 2005). Even more broadly, groundwater is a global issue connected to other global issues such as environmental degradation, climate change, and food security. Yet unlike integrated, well-mixed physical systems such as climate, groundwater storage, flow, and pumping are focused locally in aquifers [the geological formations that contain water and are able to transmit significant quantities of water under ordinary hydraulic gradient (Hiscock & Bense 2014)] that occur in specific locations. Groundwater flow and pumping in one location are likely to have a negligible effect on an aquifer across the world because the system is poorly mixed. Therefore, herein the term global scale implies aggregated, characteristic, or representative processes rather than suggesting that groundwater acts as an integrated, well-mixed physical system. The impact of groundwater pumping is most acute and obvious at local scales, and groundwater resources also have strong local characteristics related to specific hydrology, politics, laws, culture, etc. (Foster et al. 2013). Throughout this review, we focus on global aspects because these have been underrepresented in groundwater sustainability literature and because global aspects can support and complement regional efforts that we discuss in Section 4.

1.2. Scope of Review

The objective of this review is twofold: to provide a clear portrait of global-scale groundwater sustainability, systems, and resources in the Anthropocene and to provide a definition of groundwater sustainability that integrates Earth System science and groundwater governance and management. Section 2 provides a concise, yet critical, review of sustainability and natural resources. With consideration of two different yet complementary perspectives—groundwater hydrology and governance—we suggest an operational definition of groundwater sustainability. In Section 3, we provide a detailed analysis of Earth System science, emphasizing the importance of the connections between aquifers and the rest of the hydrosphere along with the atmosphere, biosphere, and lithosphere. In Section 4, we discuss the benefits of considering a global and Earth System approach in context with regional scales and governance frameworks to contribute to groundwater sustainability efforts. We began this review with the quote by Gandhi to inspire ethical use of groundwater resources.

The Anthropocene time frame is consistent with modern groundwater (Gleeson et al. 2016), but the reason for focusing on the Anthropocene is to unravel groundwater sustainability when it is most challenged rather than to focus on groundwater of a certain age. We do not discuss groundwater through deep time (Ferguson et al. 2018, Hanor 1994, Holland et al. 2013, Bethke & Marshak 1990) or even during the last glacial cycle (Lemieux et al. 2008, McIntosh et al. 2012, Person et al. 2007), although we acknowledge that groundwater systems in the Anthropocene are often impacted by climatic or geological events from well before the Anthropocene due to the long time lags of groundwater systems (Cuthbert et al. 2019a). Similarly, we focus on global groundwater processes, both natural and impacted by humans, so we primarily consider regional-scale (tens to hundreds of kilometers) and cumulative impacts rather than the impact of specific wells. For natural processes we describe fundamental groundwater process at smaller scales to contextualize these within large scales and the Earth System. We do not review the impact of pumping on individual wells because this is covered in hydrogeology textbooks (Fetter 2001, Hiscock 2005, Schwartz & Zhang 2003). All wells shown in figures represent pumping from the system of general wells rather than a specific well. By pumping we mean the removal of groundwater from an aquifer (synonymous with withdrawal or abstraction); generally, water use describes the total amount of water withdrawn from its source to be used, whereas water consumption is the portion of water use that is not returned to the original water source after being withdrawn; we use the term pumping because this is plain language.

This review is different than other recent reviews on related topics (Aeschbach-Hertig & Gleeson 2012, Bierkens & Wada 2019, Dalin et al. 2019, Wada 2016). Aeschbach-Hertig & Gleeson (2012) synthesized groundwater depletion and suggested that groundwater depletion be considered from diverse perspectives of hydrology, economics, and policy studies. Wada (2016) reviewed how groundwater depletion is modeled at the regional to global scale, whereas Dalin et al. (2019) focused on how unsustainable groundwater use is related to global food production and international trade through virtual water. Bierkens & Wada (2019) reviewed the drivers and processes related to groundwater depletion, redefining nonrenewable groundwater as well as the physical, environmental, and economic processes and limits of nonrenewable groundwater. In general, we more holistically consider groundwater from multiple perspectives of sustainability, resources, and systems, and we specifically advance new definitions of groundwater sustainability and introduce and argue for groundwater resources and sustainability within an Earth System context.

The threats to groundwater sustainability described in Section 1.1. motivate our review, but we do not further describe them in detail like other reviews (Aeschbach-Hertig & Gleeson 2012, Bierkens & Wada 2019), in part because finding positive approaches and elements to challenging problems, such as groundwater sustainability, is important to motivate change (Bennett et al. 2016). We do not explore in any detail related and important concepts such as water security (Foster & MacDonald 2014), groundwater economics (Bierkens & Wada 2019), food security (Dalin et al. 2019), virtual water (D'Odorico et al. 2019), and the food-energy-water nexus (Cai et al. 2018, D'Odorico et al. 2018, Endo et al. 2015, Scanlon et al. 2017b). We include groundwater quality as part of groundwater sustainability and acknowledge that groundwater quality is an important aspect of groundwater in the Earth System; Foster & Chilton (2003) include a preliminary review of groundwater quality and contamination, but global groundwater quality and integrating groundwater quality and quantity are both significant research gaps that we do not address but return to in the section titled Future Topics. We discuss the ecological role of groundwater at or above the surface but not subsurface groundwater ecosystems because these have been previously reviewed (Danielopol et al. 2003). We do not discuss at length groundwater and global change including climate change (Green et al. 2011, Taylor et al. 2013, Treidel et al. 2011) and land-use change (Scanlon et al. 2005, Stonestrom et al. 2018), although by focusing on the Anthropocene we consider that groundwater sustainability, resources, and systems are inherently impacted by and related to the processes of global change. We do not focus on groundwater use before the Anthropocene, so we refer readers to other resources such as those in early human evolution or early history (Cuthbert et al. 2017, Mays 2013).

2. GROUNDWATER SUSTAINABILITY AND RESOURCES

2.1. What Are Sustainability and Natural Resources?

Sustainability and the related concept of sustainable development are both poorly defined but popular to use—and popular to critique. The concept of sustainable development is generally "meet[ing] the needs and aspirations of the present without compromising the ability to meet those of the future" (World Comm. Environ. Dev. 1987, p. 9), which is a foundation of the widely adopted UN SDGs. The concept of sustainable development has been significantly critiqued as an oxymoron because economic development is often not sustainable (Robinson 2004). Sustainability does not have a universal definition but is generally considered a socioecological pursuit of a common ideal through the balancing of interconnected environmental, economic, and social pillars. Practically, pursuing a common sustainability ideal often involves setting goals, targets, or objectives. One major critique of sustainability, like sustainable development, is that the economic pillar often supersedes the environmental and social domains so that sustainability is critiqued as green-washing (Robinson 2004). An important distinction is between weak sustainability, where all forms of capital (natural, economic, etc.) can be substituted, and strong sustainability, where some natural capital stocks are nonsubstitutable and thus must be maintained independent of the growth of other forms of capital.

Resources are generally considered a source or supply from which a benefit is produced but are defined differently in diverse fields such as economics, ecology, computer science, management, and human resources; here we focus on natural resources, which are resources derived from the environment, because groundwater is a natural resource. Natural resources can be classified in different ways (Miller & Spoolman 2011): (*a*) abiotic versus biotic; (*b*) renewable versus nonrenewable; (*c*) ubiquitous versus localized distribution; (*d*) actual versus potential, given current knowledge and technology; and (*e*) economic characteristics such as rivalry and excludability (Ostrom 1990). Rivalry (or subtractability) describes how consumption by one party reduces the ability of another party to consume, whereas excludability describes if parties can be prevented from accessing a resource. Based on rivalry and excludability, natural resources can be classified as common-pool resources, private goods, public goods, or club goods. Ostrom (2007) suggests nine useful descriptors of resource systems: sector, system boundaries, size, human-constructed facilities, productivity, equilibrium properties, predictability of system dynamics, storage characteristics, and location.

From the natural resource perspective, groundwater resources are those that can be pumped to support human activities. Based on the natural resource classifications above, groundwater is an abiotic resource that occurs along a renewability spectrum from renewable to nonrenewable (see Section 2.2) that can generally be considered ubiquitous because Earth is ubiquitously saturated at some depth (although the size, productivity, and predictability of these resources vary incredibly). Herein, we generally focus on the actual resources given current knowledge and technology rather than hypothesize about potential resources, and we introduce but do not focus on the economic characteristics of groundwater as a resource. Economically, groundwater is often considered a common-pool resource that is both rivalrous and nonexcludable (Aeschbach-Hertig & Gleeson 2012, Bierkens & Wada 2019, Madani & Dinar 2012, Theesfeld 2010), which can lead to the tragedy of the commons (Hardin 1968) where groundwater depletion or contamination occurs because a large number of users share a rivalrous resource. Other useful descriptors of groundwater resources are invisible, slow moving, and distributed (Villholth & Conti 2018)—we explore the implications of these characteristics in Section 2.4.

Another useful way of describing groundwater as a resource is in comparison to surface water because surface water is a more visible and known resource. Theesfeld (2010) suggested other attributes of groundwater compared to surface water that are important in governance and management, including that (*a*) groundwater depletion or contamination can be irreversible, (*b*) there are often significant time lags between pumping and the impact of pumping, (*c*) groundwater system boundaries are often poorly constrained, (*d*) hydrogeologic uncertainty is often large, (*e*) pumping is often distributed broadly across regions, (*f*) data are often sparse and poor, and (*g*) information is asymmetrically held by organizations rather than individual users. We next review numerous concepts that have been proposed in physical groundwater hydrology to quantify groundwater sustainability of resources.

2.2. Limitations of Previous Concepts in Physical Groundwater Hydrology

Here we review the limitations of several concepts that are commonly used in the context of assessing groundwater use: safe yield, renewability, depletion, and stress (**Figure 1**). We then build on these important concepts in a new definition of groundwater sustainability (Section 2.3).

Early thinking regarding the limits of groundwater pumping led to the concept of safe yield, defined by Theis (1940, p. 280) as "the amount of rejected recharge plus the fraction of natural discharge it is feasible to utilize," drawing on previous work (Lee 1915, Meinzer 1923). Subsequently, the term has been redefined and discussed several times, which has led to some confusion over its intended meaning in different contexts (Kalf & Woolley 2005, Loaiciga et al. 1996, Todd 1959). Related terms such as basin yield or optimal yield have also been proposed and have historically been focused on economic and legal aspects of groundwater development. Despite more recent expansion of safe yield concepts to include a wider range of environmental considerations (Alley &

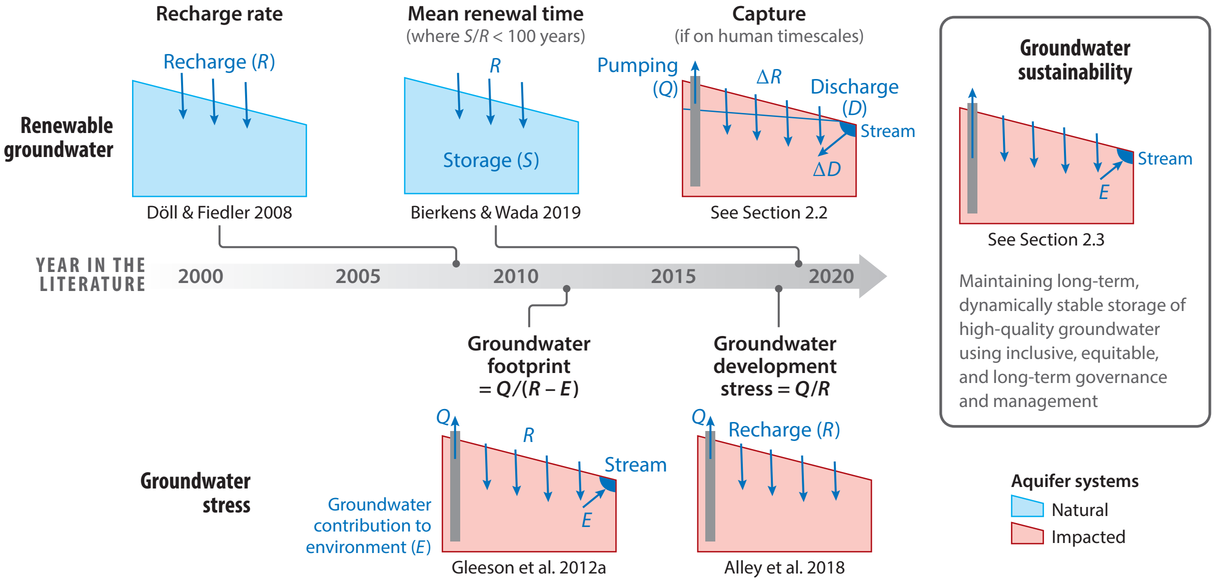


Figure 1

The evolution of the key terms renewable groundwater, groundwater stress, and groundwater sustainability. The blue water table line is not included in most of the diagrams because it is not explicitly considered in definitions of renewable groundwater or groundwater stress.

Leake 2004), the concept is still a long way from a coherent and broad definition of sustainability we propose below.

Groundwater is often thought of as existing along a spectrum of renewability due to its widespread natural replenishment by groundwater recharge. Recharge is variably defined as "the downward flow of water reaching the water table, adding to groundwater storage" (Healy 2010, p. 3) or "water that reaches an aquifer from any direction (down, up or laterally)" (Lerner 1997, cited by Scanlon et al. 2002, p. 19); it can be anthropogenically augmented by a variety of means (including as irrigation return flows) or artificial/managed recharge (Dillon et al. 2019). However, definitions of what constitutes renewable groundwater vary (**Figure 1**). Some authors take a flux-based approach and equate the renewable portion of groundwater to mean annual groundwater recharge (Döll & Fiedler 2008, Richey et al. 2015, Wada et al. 2010). Others take a storage-based approach and define groundwater in a particular location as renewable if the stored groundwater volume divided by the current rate of groundwater recharge is less than an arbitrarily defined threshold (e.g., 50 to 100 years, known as the mean renewal time) (Bierkens & Wada 2019, Margat et al. 2006) (**Figure 1**). Both definitions are problematic because using the rate of pre-pumping recharge propagates the so-called water budget myth (Bredehoeft 2002) because the definitions ignore the potential changes in recharge that may occur during capture [the increased recharge and decreased discharge due to pumping (Bredehoeft & Durbin 2009, Konikow & Leake 2014, Lohman 1972)]. They also ignore variations in recharge due to changes in climate, land use, or human interventions such as managed aquifer recharge. The flux-based definition is problematic for groundwater systems with a long time to capture because storage recovery rates on cessation of pumping may be greater than human timescales despite input and output fluxes eventually being in balance during long-term pumping. The storage-based definition also has additional drawbacks, as noted by Bierkens & Wada (2019) and Margat et al. (2006), because it requires gross approximations regarding the average distribution of residence times within an aquifer; in reality, all groundwater systems have complex distributions of groundwater residence time, which is the travel time from recharge to discharge (Kazemi et al. 2006). This is sometimes approximated as groundwater storage volume divided by recharge flux, which is equivalent to the mean renewal time (Bierkens & Wada 2019) or turnover time (Befus et al. 2017). Generally, some (often shallower) portions of the groundwater system are more actively flushed with short turnover times and some (often deeper) portions having longer flow paths and thus greater residence times (Befus et al. 2017, Tóth 1963). A further, and perhaps more fundamental, problem with the storage-based definition of renewability is the ambiguity in how the mean renewal time, as defined, is related to the storage recovery time of an aquifer, which would be a more intuitive metric for its renewability. The total storage of the groundwater system and rate of recharge are often not the primary determinants of the rate of recovery of storage (or refilling) after pumping ceases—in many cases, the hydraulic properties and boundary conditions of the aquifer are more important controls.

If we consider groundwater as a dynamically responsive system (Section 3), an improved definition of renewable groundwater may be any groundwater that can be dynamically captured during pumping that leads to a new dynamically stable equilibrium in groundwater levels within human timescales (∼100 years). By dynamically stable we mean a statistically defined range of variability around a central tendency within which a natural or impacted groundwater system fluctuates; we acknowledge that defining statistical ranges is challenging in the nonstationary Anthropocene. This way of thinking about renewable groundwater integrates previous divergent definitions described above by considering both the dynamic balance of recharge and discharge fluxes, while it also includes changes in groundwater storage and recovery that may occur on human timescales. Note that here by discharge we mean the flux of groundwater from the subsurface to above ground, in either terrestrial or aquatic environments; often in hydrology, streamflow is also confusingly called discharge, but herein we use the term streamflow for that component. Such a modified definition of renewable groundwater therefore implies that (*a*) no aquifer, volume of stored groundwater, or flux of recharge can be considered renewable without specifying a location, rate, and timing of pumping; (*b*) the groundwater response time (GRT) (Cuthbert et al. 2019a) is important to consider because some lowering of groundwater levels is unavoidable during the time to capture (Bredehoeft & Durbin 2009)—such declines do not necessarily imply a situation of nonrenewability unless the time to capture, and thus time to recover, is greater than a relevant human timescale; (*c*) the groundwater age [the time elapsed since a particular groundwater molecule was recharged (Kazemi et al. 2006)] of the water being pumped, or mean residence time of the aquifer, is not inherently relevant to its renewability, although the age distribution of groundwater in the system will be altered by pumping, which may be relevant to other criteria for pumping being sustainable such as water quality; and (*d*) an assumption of future changes (or lack of) in climate and land use and how they may alter recharge rates, and consideration of managed aquifer recharge as an input, must be taken into account in the assessment. Although we offer this definition as a more hydraulically robust development of previous definitions, the concept of groundwater renewability is still of limited use for informing a definition of groundwater sustainability because many groundwater systems have response times much longer than human time frames. Thus, such systems may be pumped at physically sustainable (see below) rates while still leading to long-term storage changes that would be considered nonrenewable.

Definitions also vary regarding the term groundwater depletion. For example, it may be very broadly defined as "the inevitable and natural consequence of withdrawing water from an aquifer" (Konikow & Kendy 2005, p. 317), which is the definition generally followed in the regional-scale streamflow depletion and capture literature (Barlow & Leake 2012, Konikow & Leake 2014).

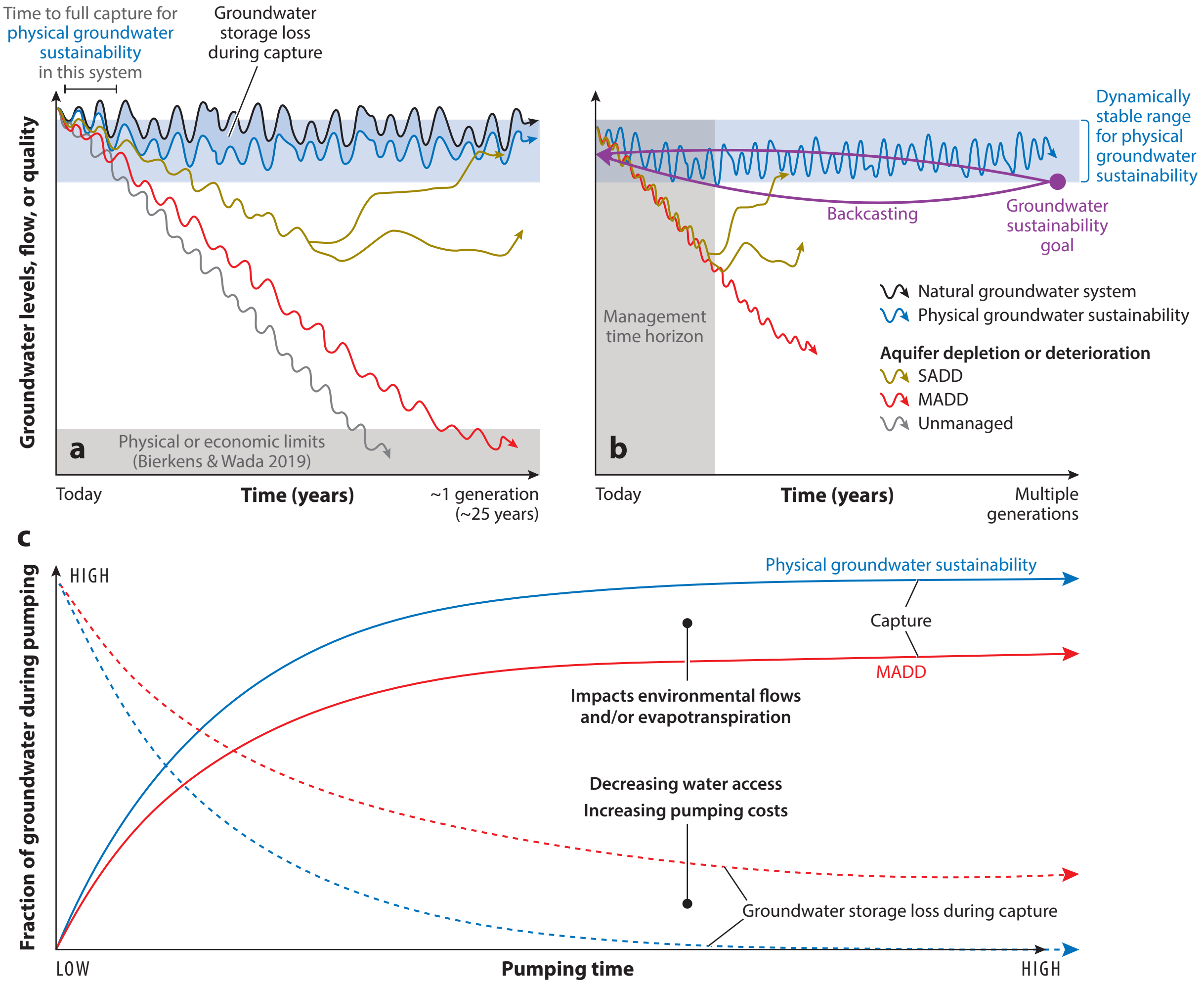


Figure 2

Groundwater sustainability. (*a*) Physical groundwater sustainability. The blue physical groundwater sustainability line deviates from the black natural groundwater system line for some time until time to full capture. This scenario assumes no change in long-term groundwater recharge. (*b*) Setting long-term groundwater sustainability goals that can then use backcasting to determine which actions are necessary in the management time horizon. Note that the timescales in panel *b* are longer than the timescale in panel *a*. (*c*) The source of groundwater to wells during pumping contrasting physical groundwater sustainability and managed aquifer depletion. Solid lines represent the capture, and dashed lines represent the groundwater storage loss during capture—that is, the groundwater storage loss that is inevitable and necessary when pumping groundwater from a well by inducing a hydraulic gradient toward the well (Konikow & Leake 2014). Abbreviations: MADD, managed aquifer depletion or deterioration; SADD, strategic aquifer depletion or deterioration.

Alternatively, groundwater depletion is also more narrowly defined as the persistent decline in groundwater levels due to physically nonsustainable groundwater use (Bierkens & Wada 2019), which is the generally followed definition in the global hydrology literature (Döll et al. 2014, Wada 2016, Wada et al. 2012). If we use the second definition, pumping may be physically sustainable (Bierkens & Wada 2019) if it will eventually lead to the establishment of a new hydraulic equilibrium where water levels are dynamically stable (**Figure 2**). This is akin to some definitions of safe yield referenced above, although we note that physical sustainability is just one part of the more holistic definition of groundwater sustainability we propose below. It is important to note that the time it takes for this new equilibrium to be established [known as the time to full capture (Bredehoeft & Durbin 2009)] may be very long—decades, centuries, or even millennia—in many groundwater systems (Cuthbert et al. 2019a, Rousseau-Gueutin et al. 2013). Thus, although the pumping may be physically sustainable, the storage decline during this transition period to reach a new equilibrium [sometimes known as the transitional storage reserve (Bredehoeft & Durbin 2009)] may lead to apparent long-term groundwater level declines that would not be considered as depletion using the second definition of groundwater depletion. Thus, groundwater depletion is another variably defined term that can cause potential confusion unless it is understood that observed declines in groundwater level, over even multidecadal timescales, are not sufficient evidence in themselves of physically nonsustainable groundwater use.

Once groundwater is pumped, the system is said to be along a spectrum of groundwater stress (**Figure 1**). Again, several definitions and indicators for groundwater stress have been proposed, as summarized by Alley et al. (2018). For example, groundwater development stress may be defined as (*a*) the ratio of long-term average annual pumping (Q) to the long-term average annual recharge (R)—i.e., Q/R; (*b*) the rate of long-term groundwater storage change (dS/dt) to long-term average recharge—i.e., $(dS/dt)/R$ (Richey et al. 2015); or (*c*) the groundwater footprint (Gleeson et al. 2012a), which is calculated as $Q/(R - E)$, where E is the long-term average environmental flow requirements derived from natural groundwater discharge. $R - E$ is sometimes referred to as the available groundwater resource (EU 2000, Hulme et al. 2002). Although there seems to be broad spatial agreement in the results of these metrics (Gleeson et al. 2012a, Richey et al. 2015, Wada & Heinrich 2013), they also have many shortcomings. For example, the use of one value of recharge is at odds with the fact that recharge may change in systems subjected to pumping or climate and land-use change. Furthermore, the often large-scale spatial integration of these metrics can mask local-scale variability, which may be important for water management (Alley et al. 2018).

The inconsistent definitions and uses of the above concepts in part stem from the difficulties in application of terminology derived from the management of other natural resources such as energy and forestry; groundwater is a flowing dynamic and sometimes complex system (see below), which makes applications of certain concepts and metrics unwieldy and sometimes nonintuitive. In addition, there is often a lack of a direct link between these concepts and observable data (water levels, flows, or quality) or groundwater functions and services. Thus, here we argue that the coherent overarching framework of groundwater sustainability is therefore more important and useful for groundwater governance and management than the concepts of safe yield, renewability, depletion, or stress (**Figure 1**).

2.3. Refining the Definition of Groundwater Sustainability

All previous definitions of groundwater sustainability (Alley & Leake 2004, Gleeson et al. 2012b, Hiscock et al. 2002) have centered around the ambiguous balancing of environmental, economic, and social pillars in a generally weak sustainability framework. For example, weak sustainability could be used to argue that groundwater depletion or contamination (the deterioration of natural capital) could be substituted for economic growth or social benefits. It is also important to consider that the term groundwater sustainability defines sustainability for a physical resource or stock. Purely physically based definitions, such as some definitions of safe yield or physical groundwater sustainability as described above, are too narrow because they do not include diverse social and environmental aspects. But in contrast, previous arguments of social sustainability justifying groundwater mining (Foster & Loucks 2006) lack a physical basis and can strangely lead to considering a practice sustainable that clearly cannot be sustained. Other important considerations for groundwater sustainability exist (Gleeson et al. 2012b) including that (*a*) groundwater use nearly always impacts the environment because groundwater is derived from storage or capture, (*b*) the management of groundwater and surface water should be integrated but often is not, (*c*) decisions about groundwater use are value driven, (*d*) a long-term or multigenerational perspective is useful, and (*e*) groundwater should be managed adaptively and inclusively by diverse actors.

Based on the above critiques and considerations, we suggest a new definition of groundwater sustainability that is consistent with, but more easily operational than, previous definitions as follows: Groundwater sustainability is maintaining long-term, dynamically stable storage and flows of high-quality groundwater using inclusive, equitable, and long-term governance and management. In this definition, the crucial functions and services provided by groundwater rest on two foundations: a physical basis (dynamically stable storage affecting groundwater levels and flows, and also water quality as can be visualized in **Figure 2**) and equitable governance and management. The functions and services are derived from previous groundwater sustainability definitions and priorities (Alley & Leake 2004, Counc. Can. Acad. 2009, Downing 1998, Gleeson et al. 2012b, Hiscock et al. 2002) as well as water law in various jurisdictions (CWC 2014, EU 2000). This definition is general enough that it can be applied to any region or jurisdiction globally. This is a stronger sustainability definition because it implies that part of groundwater natural capital stocks is nonsubstitutable, but it also allows for significant regional control through equitable governance and management and defining goals, targets, and objectives. The physical basis, governance, management, functions, and services together can provide tangible goals, targets, or objectives through which this definition can be applied, as we explore in Section 4. We emphasize that a long-term perspective is important to groundwater sustainability (**Figure 2*b***) because groundwater has long response times.

Because Section 1.1 highlighted that groundwater depletion and contamination are common in many regions of the world, it is important to describe and consider other alternative nonsustainable pathways, namely managed aquifer depletion or degradation (MADD) and strategic aquifer depletion or degradation (SADD) (**Figure 2**). Managed aquifer depletion is persistent declines that are managed to reduce the rate of decline with the intention of extending the usable lifespan of the aquifer. Managed aquifer depletion is institutionalized in various jurisdictions such as the US state of Texas (Gleeson et al. 2012b). Excellent overviews of the hydrologic, social, economic, ethical, and policy implications and considerations of managed aquifer depletion (sometimes called planned depletion or groundwater mining) can be found elsewhere (Foster & Loucks 2006, Kresic 2009, Sahuquillo et al. 2005). Some have argued that groundwater mining is a reasonable action if the reserves are well known and guaranteed to last for a long time, the environmental impacts are properly assessed and clearly less significant than the economic benefits, and the alternative solutions are envisaged for after the aquifer is depleted (Custodio et al. 2016). Strategic aquifer depletion (sometimes called planned recovery) is temporary depletion (on an approximate decadal scale) to strategically use groundwater—for example, to respond to drought. In theory, a situation of stable groundwater levels can come about as a result of economically limited pumping where wells become dry, and we note this as an exception to the rule that stable groundwater levels may be indicative of sustainable rates of pumping. Next we discuss groundwater governance and management because these are critical to implementing the definition of groundwater sustainability.

2.4. Implementing Groundwater Sustainability with Governance and Management

Governance and management are critical components of sustainability. These components are sometimes conflated, but governance is distinct from, and a prerequisite for, management. The term governance is evolving, especially with regard to surface water and groundwater resources (Villholth & Conti 2018). As a result, there are numerous definitions of water governance and groundwater governance. Generally, water governance definitions include the processes of decision-making through institutions involving multiple actors at a range of scales to define resource goals and the rules and practical measures defined to meet those resource goals (Hornberger & Perrone 2019, Lautze et al. 2011, Pahl-Wostl et al. 2013). Herein we use the following definition of groundwater governance as the "overarching framework of groundwater use laws, regulations, and customs, as well as the processes of engaging the public sector, the private sector, and civil society . . . [that] shapes how groundwater resources are managed and how aquifers are used" (Megdal et al. 2015, p. 678). Management is the implementation of rules and measures that have been outlined by governance to achieve the defined goals. Water management includes the practical, day-to-day activities that promote the water governance framework; as a result, water management is more limited in scope and includes fewer actors than water governance (Villholth & Conti 2018). More specifically, groundwater management is the implementation of established rules and measures to develop and use groundwater resources sustainably (UN FAO 2016).

Groundwater governance contains four key elements: effective institutions that integrate stakeholders; policies and capital that support local, regional, and global resource goals; legal systems with the capacity to create and implement laws effectively; and local knowledge, customary or cultural context, and scientific understanding of groundwater systems (UN FAO 2016):

1. Institutional arrangements are the global, national, regional, or local formal or informal rules, norms, and beliefs we use to frame or organize our actions (Ostrom 2005). Groundwater institutions "define and affect instruments devised to manage groundwater" (Kemper 2007, p. 154). Some examples of instruments include water rights, well construction and groundwater withdrawal permits or licenses, metering or monitoring, tariffs or subsidies, and groundwater markets (Mukherji & Shah 2005). Groundwater institutions can have a range of organization forms, including national, regional, or local government agencies and groundwater user associations (Kemper 2007).
2. Generally, policy includes strategies and plans adopted by stakeholders (e.g., government, business, individuals) used to guide decision-making processes. In the context of this review, groundwater policy includes the actions used to guide decision-making processes toward groundwater sustainability (Varady et al. 2013). For example, policies used to manage groundwater could include equal access to water for all, short-term economic development, and conservation (Sagala & Smith 2008). Putting policies into place requires instruments such as laws, economic incentives, and behavioral change campaigns. As a result, both human and economic capital are critical for the creation, implementation, and maintenance of policies (Araral & Yu 2013).
3. The objective of a legal system for groundwater withdrawals is to prevent or resolve disagreements through formal standards and guidelines and associated penalties for noncompliance (Hornberger & Perrone 2019). An effective legal system requires strong implementation processes such as measures to identify noncompliance. For example, in the United States laws written and enacted by the legislature fall under statutory law. Statutes are often broad, providing a regulatory framework but not detailed information on how the law is applied and enforced. Details regarding the application and enforcement of the laws are often done through the rule-making process such as regulations, which have the force of law.

4. Local and regional information is critical to define good groundwater governance. Generally, there is a positive relationship between the wealth of countries and their advancement of governance and management (Villholth & Conti 2018). In places where data are limited and laws have not been formally established, management may be limited, but governance can still be established or evolving through local knowledge of aquifers and customary procedures (Villholth & Conti 2018).

Within the context of these four key elements, equitable groundwater governance (Goff & Crow 2014, Sen 2000) is an important consideration. Equity is more holistic than equal access to groundwater quantities (Lu et al. 2014, Phansalkar 2007). Equitable groundwater governance accounts for global and local norms associated with access to groundwater for a range of uses, including drinking, household activities, and livelihood activities (Goff & Crow 2014). Nevertheless, achieving equitable groundwater governance is challenging for many of the same reasons groundwater is such a vital resource globally. Groundwater is invisible and slow moving, allowing it to be protected and stored in large quantities in the subsurface, but it is also difficult to understand scientifically (Villholth & Conti 2018). Groundwater is distributed and therefore accessible to rural or disadvantaged communities that have few resources to invest in large-scale infrastructure. Nevertheless, the distributed aspect of groundwater accentuates the roles of humans, their preferences, and their norms. Although the distributed nature of groundwater provides opportunity to incorporate local social, cultural, and political preferences, it also opens the door to fragmentation. A recent survey of the United States found that groundwater governance was fragmented, with vast differences among states and their management priorities (e.g., consideration of ecosystems), establishment of legal frameworks, and capacity to implement and enforce policies (Megdal 2018, Megdal et al. 2015). The Groundwater Governance project has revealed similar findings when looking globally (Villholth & Conti 2018), although the European Union Groundwater Directive and Water Framework Directive (EU 2000) show that nations with different backgrounds and priorities can agree on common policy and legal frameworks. In short, groundwater is invisible, slow moving, and distributed, creating challenges for equitable governance and Earth Systems science alike.

Because groundwater transcends jurisdictional boundaries, increasing international cooperation in groundwater governance (Hoekstra 2017) could be useful for moving sustainability forward. For example, institutionalizing caps on groundwater footprints or environmental baseflow requirements, as well as incorporating water sustainability in product labels or investment decisions, could all benefit from enhanced international cooperation on groundwater governance.

Next, in Section 3, we explore the nature of groundwater systems within the context of the Earth System because this can provide a more holistic and larger-scale perspective before returning in Section 4 to consider how groundwater sustainability could be complemented or expanded with an Earth System perspective.

3. GROUNDWATER SYSTEMS AND THE EARTH SYSTEM

3.1. What Are Complex Systems and the Earth System?

A system is generally defined as a set of things working together as parts of a mechanism or an interconnecting network, whereas complex systems are systems composed of many components that interact strongly with each other; are often nonlinear and nested; and can have memory, feedbacks, and emergent behavior (Thurner et al. 2018). Complex systems generally have boundaries that can be open and fuzzy as well as inputs, outputs, and relationships between components. The Earth System is often considered a complex system (Rockström et al. 2009; Scheffer et al. 2009, 2012; Steffen et al. 2018) composed of different components such as the hydrosphere, lithosphere, atmosphere, and biosphere. Here we are primarily focused on one of the stores of the hydrosphere, groundwater, and the interactions of this store with other components of the Earth System. Important types of complex systems in resilience literature are socioecological systems, which are integrated systems of ecosystems and human society with reciprocal feedback and interdependence (Folke et al. 2010). Below we consider both natural and impacted groundwater systems, where pumping is the primary impact considered herein. We focus on basic system characteristics such as boundaries, stores, inputs, and outputs. Groundwater systems have not generally been considered as complex systems, but groundwater governance, especially if considered a socioecological system in resilience literature, can be considered a complex system (Rica et al. 2018).

3.2. Approaches to Characterizing Global Groundwater Systems

Three approaches have been pioneered in the last 10 years to characterize the continental- to global-scale interactions between groundwater and the other components of the Earth System and quantify various aspects of groundwater sustainability:

1. Several global hydrological models, land surface models, and Earth System models now incorporate groundwater processes to varying degrees of complexity, as has been recently reviewed by Gleeson et al. (2019), who cataloged model characteristics. These numerical models are built for diverse purposes but share the ability to carry out water balance calculations at the land surface to estimate groundwater recharge. Several regional-global models also explicitly include the two-dimensional (2D) transient redistribution of groundwater flow (**Figure 3*c*,*d***).
2. Currently such global numerical models are computationally expensive and do not include all physical processes that are relevant to some Earth System or sustainability problems, such as density-dependent groundwater flow. The computational expense makes it challenging to rigorously quantify the uncertainties due to the coarse-scale global data sets on which they are based and the choice of model structure simulated. Hence, another approach that has recently been adopted is the use of mathematical analytical models (Cuthbert et al. 2019a); although they are inherently more simple in their assumptions and processes that can be included, these allow for a much more extensive uncertainty analysis to be carried out due to being much more computationally efficient (**Figure 3*a***). Another recent approach is synthesizing a large number of local numerical models that include all crucial physical processes. For example, Luijendijk et al. (2019) used local numerical models including density-dependent groundwater flow to quantify the spatial distribution and global flux of submarine groundwater discharge (**Figure 3*b***). These numerical models were geometrically simple (2D cross sections rather than 3D groundwater flow) but included all the relevant physical processes and allowed for sensitivity analysis.
3. Remote sensing, in particular measurements of changes in Earth's gravity field by NASA's Gravity Recovery and Climate Experiment (GRACE) satellite, has provided insights into changes in groundwater storage due to pumping (Famiglietti 2014, Rodell et al. 2009) and changes in climate (Thomas & Famiglietti 2019). Previous estimates of large-scale shifts in groundwater storage typically required integration of large numbers of point measurements from individual wells or estimation through numerical modeling (Konikow 2013). Working between the low-resolution (~200,000-km^2) data from GRACE and the higher resolution required for many hydrogeological studies remains a challenge, but progress is currently being made on downscaling techniques (Miro & Famiglietti 2018).

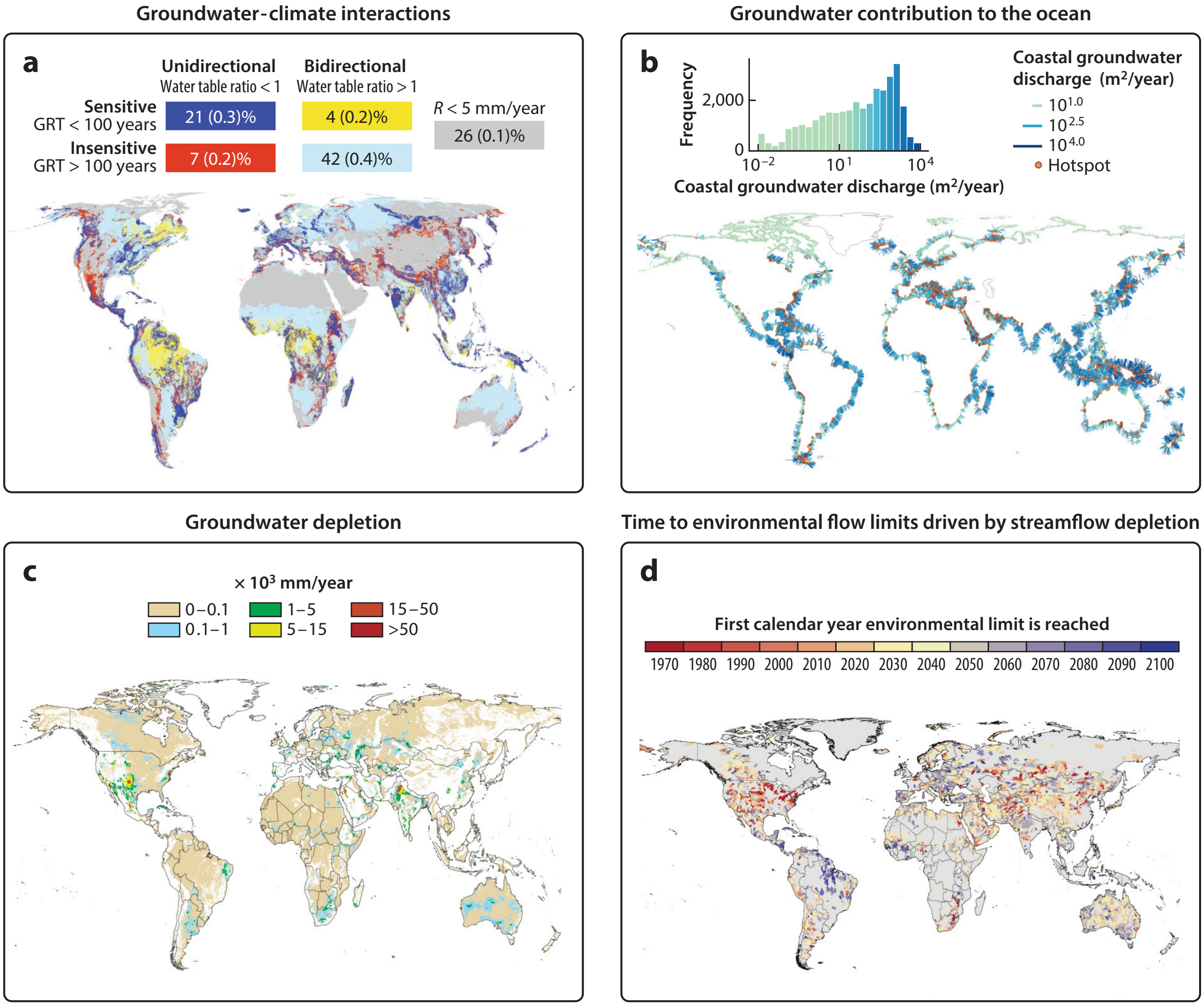
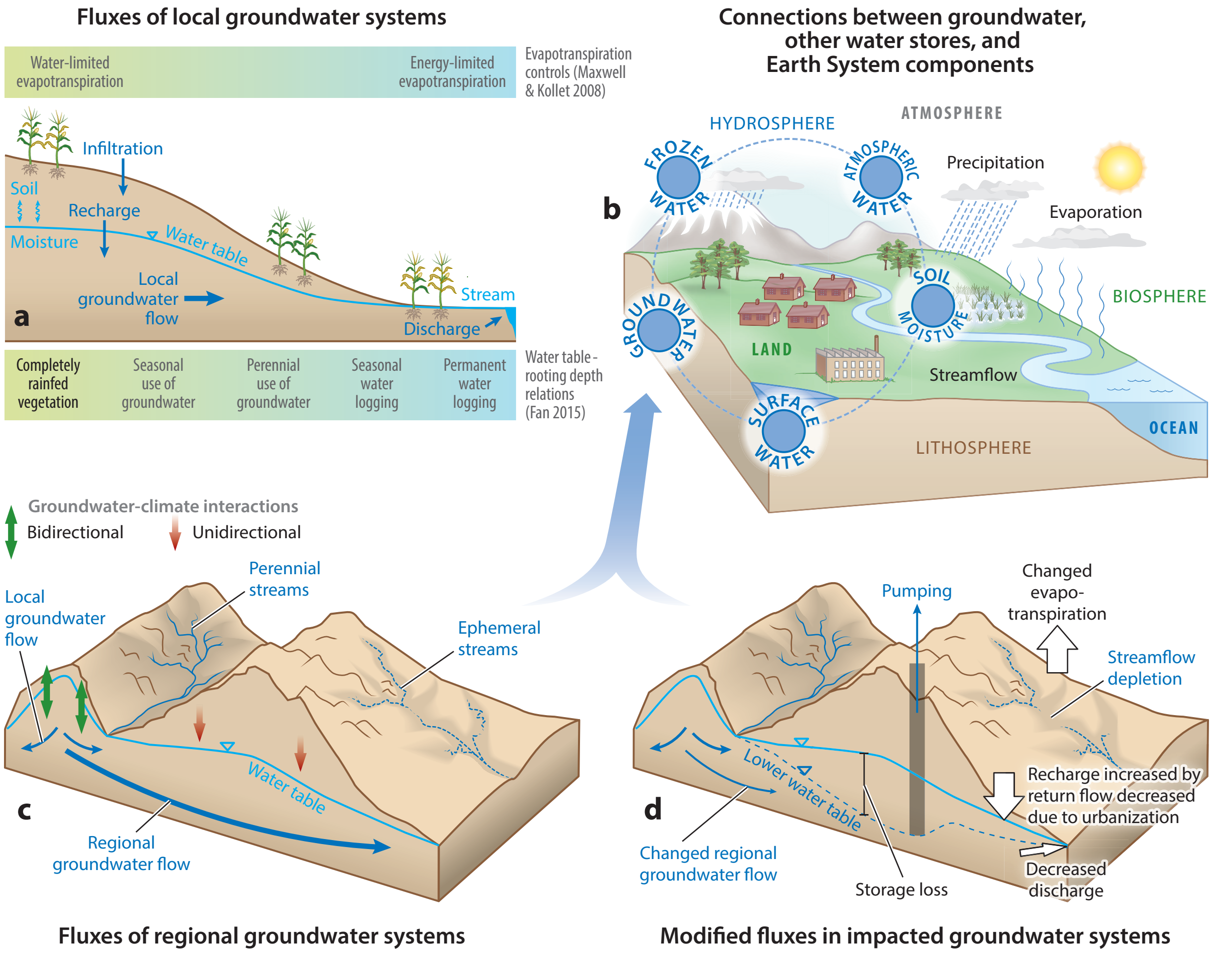


Figure 3

The global distribution of natural and impacted groundwater systems. (*a*) Groundwater is connected to various Earth Systems such as climate (see Cuthbert et al. 2019a for descriptions of the terms). (*b*) Groundwater contributes to the ocean through CGD (see Luijendijk et al. 2019 for descriptions of the terms). Groundwater pumping leads to (*c*) groundwater depletion (de Graaf et al. 2017) and (*d*) streamflow depletion, which impacts environmental flows on different timescales (de Graaf et al. 2019). Abbreviations: CGD, coastal groundwater discharge; GRT, groundwater response time. Panel *a* adapted from Cuthbert et al. (2019a). Panel *b* adapted from Luijendijk et al. (2019). Panel *c* adapted from de Graaf et al. (2017). Panel *d* adapted from de Graaf et al. (2019).

3.3. What Are the Crucial Fluxes and Characteristics of the Groundwater System?

Groundwater is the largest store of liquid freshwater on Earth (Alley et al. 2002, Gleeson et al. 2016) and is a dynamic system (Alley et al. 2002) with groundwater recharge as input. Recharge is controlled by a complex set of natural processes, and its magnitude and timing are influenced principally by land cover, topography, soil type, geology, and climate, but it can also be affected by groundwater pumping (**Figure 4**). Diffuse recharge occurring in a spatially distributed manner over the land surface tends to dominate in more humid regions where precipitation



Fluxes of local groundwater systems

Connections between groundwater, other water stores, and Earth System components

Fluxes of regional groundwater systems

Modified fluxes in impacted groundwater systems

Figure 4

Natural and impacted groundwater systems and connections with the Earth System. (*a*) Important fluxes for local groundwater systems not including focused recharge or preferential flow (< ∼10-km length scale) (Fan 2015, Maxwell & Kollet 2008). (*b*) The connections between groundwater and other water stores in the hydrosphere (streamflow, soil moisture, frozen water, and atmospheric water) as well as other parts of the Earth System including the biosphere and lithosphere. For the volume of each store or the fluxes between them, see most hydrology textbooks. (*c*) Important fluxes and characteristics of regional groundwater systems (> ∼10-km length). (*d*) Modified fluxes in impacted groundwater systems. Panel *b* adapted from Gleeson et al. (2020). Panel *c* adapted from Cuthbert et al. (2019a). Panel *d* adapted from Aeschbach-Hertig & Gleeson (2012).

regularly exceeds soil moisture deficits and evaporative demands (Healy 2010). In more arid regions, only periods of particularly intense precipitation can cause diffuse recharge to occur. More commonly, spatial accumulation of water from runoff into streams or other water bodies is needed to enable recharge in more arid regions, known as focused (or indirect) recharge (Cuthbert 2019b, Scanlon et al. 2006). The input of recharge to the groundwater system sets up a hydraulic gradient under which groundwater flows naturally under gravity toward topographic low points where it discharges as submarine discharge to coastal areas; baseflow to lakes, rivers, and streams; evapotranspiration to playas or phreatophytic vegetation; or discrete discharge to springs.

The groundwater flow field can be strongly controlled by the geological structure insofar as this determines the pattern of hydraulic properties such as permeability and storage through which flow occurs. Where flow systems are not complicated by such structures, they are typically nested with local-scale systems developing near the surface that recharge and discharge in the same watershed and larger, regional-scale systems with groundwater fluxes between watersheds at depth (Tóth 1963). Geological features such as low permeability deposits or faults may create physical boundaries that delineate groundwater flow fields, and zones of recharge and discharge create other more dynamic and even spatially varying hydraulic boundaries.

Many different system metrics for groundwater systems could be useful for different purposes—we consider here some metrics for large-scale natural groundwater systems. For example, the ratio of transpiration to evaporation in hydrologic models reveals that both latent heat flux and partitioning of evaporation and transpiration are connected to water table depth and impacted by lateral groundwater flow (Maxwell & Condon 2016) and groundwater depletion (Condon & Maxwell 2019). The water table ratio (WTR) describes the relationship between the water table, topography, recharge rate, and flow system dimensions (Gleeson et al. 2011, Haitjema & Mitchell-Bruker 2005). The GRT is a measure of how long a groundwater system will take to equilibrate to new hydraulic boundary conditions (Cuthbert et al. 2019a). Both the WTR and the GRT help to characterize the distribution of hydraulic heads in groundwater systems. As shown in **Figure 3*a*** and described further below, these two metrics can be usefully combined to illustrate the extent and timescales of the interactions between groundwater and climate. Other metrics, such as groundwater age and residence time (Bethke & Johnson 2008, Phillips & Castro 2003), can be used to characterize the timescales of groundwater flow and solute transport. Hydraulic and transport processes are linked because differences in hydraulic head typically drive advective transport of solutes. However, diffusion of hydraulic signals through groundwater systems (i.e., determining GRTs) typically occurs much more rapidly than solute transport (which determines groundwater residence times and ages).

3.4. What Are the Crucial Connections Between Groundwater and Other Components of the Earth System?

Despite groundwater's large volume, the fluxes between groundwater and other compartments of the hydrologic cycle are relatively small compared to those on and above Earth's surface. Although these fluxes are often small, they can be of critical local importance in nutrient (Hayashi & Rosenberry 2002) and elemental cycling (Ferguson & McIntosh 2019, Stahl 2019), regulating temperature (Powers et al. 1999), and maintaining streamflow during low flow periods (Winter 2007). The various inputs, outputs, boundaries, and stores described above interact with each other in a dynamic and nonlinear way, creating globally diverse, complex, and dynamic groundwater systems with multiple feedbacks with other parts of the Earth System. Below we describe in more detail the connections between groundwater and the biosphere and the rest of the hydrosphere, atmosphere, and lithosphere and how these connections are impacted by pumping (**Figure 4**).

3.4.1. Biosphere and the rest of the hydrosphere. Groundwater and the biosphere are intertwined, with the most obvious connections occurring in groundwater discharge areas, which can support groundwater-dependent ecosystems and human uses and be sensitive to the impacts of pumping in different ways (Gleeson & Richter 2018, Mukherjee et al. 2018) (**Figure 4**). This may be due to reductions in flow rates or variations in water chemistry or temperature. When groundwater discharges to lakes, wetlands, rivers, and streams, it provides a stabilizing influence on their flow regimes, critically providing baseflow during seasonally or climatically dry periods when quickflow from shallow surface or subsurface runoff is limited. Baseflow and related biogeochemical and thermal exchanges with surface water within the hyporheic zone support a diverse range of hydroecology (Griebler & Avramov 2015, Hayashi & Rosenberry 2002). Groundwater also discharges in a more spatially discrete way in a variety of settings to springs (Springer & Stevens 2009), which are often associated with dependent vegetation or even wetlands. Where water tables are shallow enough, plants known as phreatophytes directly abstract shallow groundwater, and changes in the rates of groundwater discharge will therefore directly impact the productivity of such vegetation that may be ecologically sensitive (Batelaan et al. 2003). Finally, the subsurface itself is home to a diverse array of ecosystems from bacteria, fungi, and archaea to worms, rotifers, and arthropods (Danielopol et al. 2003). Although poorly understood, the impacts of pumping and subsequent changes in saturation and groundwater chemistry can lead to changes in connected food webs (Schmidt et al. 2017).

The impacts of groundwater pumping on the biosphere and the rest of the hydrosphere are a function of capture and depletion as described above in Section 2.2. Most global groundwater models to date have focused on groundwater depletion (**Figure 4*c***), and these efforts have been reviewed by Bierkens & Wada (2019). More recently, these global groundwater models have quantified streamflow depletion and the timing impacts of groundwater pumping on environmental flows (**Figure 4*d***). The results suggest that, by 2050, environmental flow limits will be reached for approximately 42% to 79% of the watersheds in which there is groundwater pumping worldwide; this will generally occur before substantial losses in groundwater storage are experienced, which has significant implications for the distribution and sensitivity of aquatic ecosystems to groundwater pumping (de Graaf et al. 2019).

3.4.2. Ocean. Submarine groundwater discharge is an important source of water and solutes to the world's oceans. Estimates of the global volume of submarine groundwater discharge vary widely, with some studies suggesting values as high as 10% of overall terrestrial discharge, although recent estimates suggest ∼3% (Luijendijk et al. 2019). Although submarine groundwater discharge is globally important, its distribution varies substantially and hot spots of discharge exist. In coastal areas, submarine discharges or springs and seepages within the intertidal zone are critical to a wide range of benthic and pelagic ecology (Johannes 1980) and are important to many coastal communities for drinking, hygiene, agriculture, fishing/diving, and spiritual use (Moosdorf & Oehler 2017). Discharging waters carry a range of solutes and are important to biogeochemical cycles (Slomp & Van Cappellen 2004) and contaminant transport (Burnett et al. 2003). Submarine groundwater discharge has been linked to algal bloom formation in some cases (Hu et al. 2006, Lee & Kim 2007).

Most of the world's population resides in coastal areas (Small & Nicholls 2003), and substantial population growth is expected to occur in most coastal cities over the coming decades. This concentration of population has created a large demand for groundwater in coastal areas, which has led to seawater intrusion into coastal aquifers in many regions (Barlow & Reichard 2010, Ferguson & Gleeson 2012, Werner et al. 2013) and reduction of submarine groundwater discharge (Michael et al. 2018). Seawater intrusion will be made worse globally with rising sea levels due to an increase in hydraulic head at the coast, which will cause landward migration of the freshwater-saltwater interface (Michael et al. 2013, Werner & Simmons 2009), and due to infiltration of seawater after inundation (Ataie-Ashtiani et al. 2013).

3.4.3. Atmosphere. Interactions between the atmosphere and groundwater occur variably at locations of recharge and discharge and can be characterized as having either unidirectional or bidirectional modes of interaction (**Figure 3*a***). These modes can be usefully classified using the

WTR. Values of WTR > 1 correlate globally with shallow water table depths and indicate a predominantly bidirectional mode of climate-groundwater interaction—meaning the atmosphere can receive moisture from the groundwater system via evapotranspiration but also give to the groundwater as recharge (Cuthbert et al. 2019a). In such areas, which cover approximately 46% of Earth's land surface, land-atmosphere energy exchanges can be impacted by the presence of shallow groundwater (Maxwell & Condon 2016, Maxwell & Kollet 2008). In contrast, areas with WTR < 1 are indicative of unidirectional interaction whereby the land surface is decoupled from the groundwater to such an extent that groundwater may still receive recharge from the climate but the water table is too deep to allow plants to mediate a two-way moisture and energy exchange with the atmosphere. As the climate changes, although effects on groundwater recharge may be relatively quick, regions with high GRTs [global median is approximately 1,300 years excluding hyperarid regions (Cuthbert et al. 2019a)] will be slow to show associated changes in rates of groundwater discharge as groundwater flow systems equilibrate. Broadly speaking, higher GRTs are associated with climatically dry regions and thus groundwater discharges, and therefore climate-groundwater interactions, in such regions may show a very damped response and feedback to climate change (Cuthbert et al. 2019a).

3.4.4. Lithosphere. Groundwater is known to be a key driver of weathering in the subsurface. Weathering profiles are sensitive to the position of the water table and groundwater recharge rate (Anderson et al. 2007, Jin et al. 2011). Well-known concentration-streamflow relationships demonstrate that when the bulk of streamflow originates as groundwater discharge, dissolved solids concentrations are typically greatest (Bluth & Kump 1994, McIntosh et al. 2017). Groundwater discharge is often the origin of dissolved solids in watersheds (Rumsey et al. 2017). These conclusions are often based on chemical hydrograph separation, which does not provide direct evidence of the depth of groundwater circulation. Much of this discharge comes from active shallow flow systems, but smaller fluxes of deep groundwater can often be disproportionately important to solute transport (Grasby & Betcher 2002). However, discharge of higher salinity waters is rare, and groundwater in the deep Earth is tenuously connected to the rest of the hydrologic cycle. Where meteoric water is present, it can have ages of tens of thousands to millions of years (Holland et al. 2013). Much of the water in the deep subsurface is connate and originated as seawater (Hanor 1994). Preservation of these deep waters is achieved by slow movement through low permeability strata (Ingebritsen & Manning 1999, Neuzil 1994) and negative buoyancy due to high salinities (Ferguson et al. 2018). Installation and operation of wells for water supply (Perrone & Jasechko 2017, 2019) and by the energy industry (McIntosh & Ferguson 2019, Scanlon et al. 2017a) have led to the mixing of waters of various depths and ages, but the implications of such mixing to lithospheric processes at large scales is unclear.

4. EARTH SYSTEM AND HUMAN PERSPECTIVES AT REGIONAL TO GLOBAL SCALES: DIFFERENT YET COMPLEMENTARY FOR GROUNDWATER SUSTAINABILITY

Groundwater sustainability is a complex issue where simultaneously maintaining different, yet complementary, perspectives across scales is helpful. The Anthropocene is a world of ever-increasing connection driven by global trade, evolving culture, and information exchange (Steffen et al. 2015); humans are an intrinsic part of the hydrologic system both as agents of change and as beneficiaries of water functions and services, which demands integrating human and physical perspectives (Wagener et al. 2010). In this increasingly interconnected world, we need to view groundwater both globally and regionally because groundwater operates on both scales simultaneously (Section 1). It is also important to integrate human perspectives in groundwater governance and management (Section 2.4), physical perspectives in groundwater hydrology (Section 2.2), and Earth System science (Section 3). We therefore conclude this review by discussing how insights from Sections 1–3 can be viewed or integrated across different perspectives and scales. First, we explore how regional and human perspectives are crucial to groundwater sustainability and often require that regional perspectives be integrated in a global framework; we include a description of groundwater within a global sustainability framework, the UN SDGs. Second, we explore how an Earth System perspective improves our understanding of groundwater sustainability; we include a description of groundwater within a global Earth System sustainability framework, the planetary boundaries. A recent project titled The World in 2050 highlights how goals could be set for meeting the SDGs by 2030 while staying within the planetary boundaries by midcentury (TWI2050 2018).

4.1. Human and Regional Perspectives on Groundwater Sustainability

Groundwater sustainability necessitates incorporating human perspective into governing and managing the physical resource (Alley & Leake 2004, Gleeson et al. 2012b, Van der Gun & Lipponen 2010). There is no reason to believe there is a single global solution to groundwater sustainability—the world is too diverse hydrologically, politically, culturally, and economically. Therefore, applying the proposed definition of groundwater sustainability necessitates translating a generalized definition or concept to a specific region or nation. This translation process involves defining terms (e.g., what do dynamically stable groundwater levels mean for a particular aquifer?) and start and end times, as well as setting goals, objectives, or targets that can then be used to define trajectories and policies by forecasting or backcasting. Regional differences in priorities, hydrology, politics, culture, and economic conditions mean that different governance and management tools are appropriate and effective in different regions (see the sidebar titled Important Groundwater Management Tools).

Because this is a review of global groundwater sustainability, we use how groundwater relates to Agenda 2030 of the United Nations and its 17 SDGs (see the sidebar titled Groundwater and the Sustainable Development Goals) to guide a discussion of regional differences. Considering groundwater in the SDGs is a way to globally consider groundwater sustainability, but by doing so we do not imply that national-, regional-, or aquifer-scale conditions, aspects, and characteristics are in any way unimportant. It is crucial to consider regional differences when considering the relationship between the SDGs and groundwater sustainability. In some regions, such as in parts of the Global North, many of the SDGs are met but groundwater depletion is a significant concern—in these regions, groundwater depletion should be the focus of groundwater governance and management. In other regions, such as in parts of the Global South, some of the SDGs have not been met, groundwater resources are not significantly developed, and groundwater depletion is not a concern—in these regions, considering sustainability in governance frameworks while increasing groundwater use to contribute to achieving the SDGs is likely to be important. Groundwater can be a more distributed and resilient water source compared to surface water so that groundwater could continue to enable significant socioeconomic development in these regions. Finally, in other regions, some of the SDGs have not been met, and groundwater depletion is a significant concern. These regions may have the most conflicting priorities on two levels: between SDG fulfillment and groundwater sustainability and between the conflicting relationships within the SDGs (see the sidebar titled Groundwater and the Sustainable Development Goals). In the future, SDG fulfillment could be considered a second tier of groundwater sustainability analysis and metrics in addition to the definition in Section 2.3.

IMPORTANT GROUNDWATER MANAGEMENT TOOLS

1) Long-term, adaptive, and conjunctive groundwater management plans. Groundwater is a slow and invisible resource, so long-term and adaptive plans with clear targets are essential. For example, backcasting to groundwater sustainability (**Figure 2*b***) starts with defining a desirable future and then works backward to identify policies and programs that will connect that future to the present. Conjunctive management of groundwater and surface water is also paramount because many groundwater sustainability solutions involve surface water.
2) Monitoring, metering, and reporting. A critical aspect of managing groundwater is monitoring groundwater supplies and metering groundwater demands; these activities support compliance with and enforcement of legal controls and policies (Holley & Sinclair 2013, Nelson & Perrone 2016). Reporting information obtained from metering is fundamental to make the information useful, but reporting is not necessarily required where metering is required (Nelson & Perrone 2016). Monitoring, metering, and reporting can be seen as resource intensive (requiring human and economic capital) or controversial (raising privacy concerns) (Newman et al. 2018). Remote sensing or satellite imagery are increasingly being used in places where localized information is not feasible to collect.
3) Green to gray infrastructure. Gray infrastructure includes the pipes, pumps, ditches, and detention ponds engineered to manage water, whereas green infrastructure is "the intentional use of ecological assets and/or ecosystem-based features, processes, and functions as an integral part of addressing water needs" (Climate Bonds Initiative 2018, p. 5). Gray infrastructure such as has managed aquifer recharge has long been practiced (O'Hare et al. 1986); when paired with green infrastructure, nature-based solutions can emphasize climate change adaptation or water quality.

4.2. Earth System Perspectives on Groundwater Sustainability

Although the connectedness of the Earth System provides for an intimidating start, it also provides for an opportunity. Viewing groundwater sustainability and resources from an Earth System perspective emphasizes connections between aquifers and the rest of the hydrosphere along with the atmosphere, biosphere, and lithosphere. While there have been efforts to include groundwater hydrology into Earth System models, these efforts have sought to understand how groundwater hydrology might affect other aspects of the Earth System. The strongest connections are where fluxes of groundwater are greatest, which has resulted in a focus on groundwater–surface water interaction, critical zone processes, and shallow groundwater. Groundwater pumping more typically involves slightly deeper parts of the subsurface and waters with longer residence times. Examination of groundwater sustainability and resources in an Earth System framework will require looking from pumped portions of aquifers outward, rather than simply looking at the portions of groundwater systems that are strongly connected to other Earth Systems under natural conditions. The Earth System perspective on groundwater sustainability and resources is likely more useful and interesting for holistically examining cumulative impacts of pumping on large scales. This perspective is likely less useful and interesting for examining an individual pumping well, which may be why this perspective has not been common in applied hydrogeology to date.

The various drivers and processes of global change certainly impact groundwater sustainability and resources; an Earth System perspective importantly allows the comparison of relative importance of different drivers—for example, considering human water use versus climate change, such as Ferguson & Gleeson (2012), which compared the impact of groundwater pumping versus sea-level rise on saltwater intrusion in coastal aquifers. Additionally, this approach encourages systems thinking on groundwater sustainability and resources through the connections between groundwater and the biosphere and the rest of the hydrosphere, atmosphere, and lithosphere—potentially including some systems metrics described above. Each of these processes and impacts of groundwater pumping are individually well known, but here we emphasize integrating this knowledge more holistically from an Earth System perspective to contribute to our understanding of groundwater sustainability and resources. Finally, this Earth System perspective could in the future allow for planetary-scale groundwater sustainability metrics using the planetary boundaries framework (see the sidebar titled Groundwater and the Planetary Boundaries), which could be considered a second tier of sustainability analysis in addition to the definition in Section 2.2, like the SDGs as suggested above.

5. CONCLUDING REMARKS

In sum, we urgently need a pivot toward more sustainable groundwater use in the Anthropocene, which will require holding and integrating perspectives across scales and disciplines. Considering groundwater at continental to global scales allows us to inform water management and governance for large, and often transboundary, groundwater systems in an increasingly globalized world with virtual water trade. A global perspective provides for a consistent and systematic framework that could enable prioritization of regions or knowledge transfer between regions. A global perspective, with regional-scale studies integrated within it, can promote our understanding of the two-way interactions between groundwater and the rest of the hydrologic cycle, as well as between groundwater and the broader Earth System. Finally, a global perspective allows for the creation of visualizations and interactive opportunities to improve understanding and appreciation of groundwater resources relevant to the population at large.

SUMMARY POINTS

1. Groundwater is a crucial resource for current and future generations but is not being sustainably used in many parts of the world.
2. Groundwater is distributed, slow, and invisible, which makes it accessible to rural communities but challenging to govern and manage. Groundwater governance is often fragmented, with vast differences among regions and their management priorities.
3. Sustainability can be simply and operationally defined with a direct link with observable data (water levels, flows, or quality), groundwater governance and management, and groundwater functions and services.
4. A coherent overarching framework of groundwater sustainability is more important for groundwater management, policy, and governance than the concepts of safe yield, renewability, depletion, or stress.
5. Groundwater is the largest store of freshwater on Earth and is heterogeneously connected to many Earth System processes on different timescales.
6. An Earth System approach highlights the connections between groundwater and the rest of the hydrosphere, biosphere, atmosphere, and lithosphere and how these connections are impacted by groundwater pumping.
7. Regional differences in priorities, hydrology, politics, culture, and economic conditions mean that different governance and management tools are appropriate and effective in different regions while a global perspective allows prioritization of regions or knowledge transfer between regions.

FUTURE ISSUES

1. Data synthesis, analysis and modeling of patterns, timescales and space scales, drivers of global groundwater quality, and integrating groundwater quality (including point source, nonpoint source, and novel pollutants) and quantity are needed.
2. We need to develop a holistic quantitative analysis and modeling framework that is useful for interdisciplinary groundwater sustainability goals that would move beyond the physically based models described in Section 3.2 and by Gleeson et al. (2019). This framework may include elements or linkages of agent-based models (e.g., Castilla-Rho et al. 2017), coupled groundwater-surface-atmosphere models (e.g., de Graaf et al. 2017), economic models (e.g., Kahil et al. 2018), land-use models, and an accessible user interface for water managers to run scenarios and trade-off analyses.
3. Can groundwater sustainability be a grand challenge for science and policy (Fogg & LaBolle 2006)? Or, more broadly, can groundwater sustainability be an exemplar for Earth sustainability and resilience because groundwater, like other parts of the Earth System, has a wide range of residence times, a distributed resource, and complex and heterogeneous management and governance?
4. The role and importance of groundwater in the UN sustainable development goals as well as the planetary boundaries need clarification and resolution to work toward defining a safe and sustainable operating space for groundwater (Gleeson et al. 2020). This research may integrate the role of groundwater in environmental flows (Gleeson & Richter 2018) or ecosystem services (Griebler & Avramov 2015).
5. The resilience of socioecological systems such as groundwater in irrigated agricultural watersheds is under-researched and underappreciated. Applying a resilience lens to groundwater could involve resilience across different timescales (see Weise et al. 2019).
6. Although groundwater rights are defined in many regions, exploring a global ethical framework could be considered [e.g., the "Law of the Hidden Sea" (Lopez-Gunn & Jarvis 2009)] to promote consistent, and accepted, groundwater governance across jurisdictional boundaries.
7. Emphasizing hopeful elements of existing practice offers the opportunity to motivate, accelerate, and define well-articulated pathways toward a more positive future. We need to better define groundwater-related "seeds of good Anthropocene" (Bennett et al. 2016).
8. Groundwater governance to date has been at local to national scales with few exceptions, such as transboundary aquifers and the European Union Groundwater Directive and Water Framework Directive (EU 2000). Exploring some of the benefits and possibilities of international cooperation in groundwater governance (Hoekstra 2017) or global groundwater governance as has been discussed for water more broadly (Gupta & Pahl-Wostl 2013) could be useful.

DISCLOSURE STATEMENT

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RELATED RESOURCES

1. International Groundwater Resources Assessment Centre: **https://www.un-igrac.org/**. Facilitates and promotes international sharing of information and knowledge required for sustainable groundwater resources development and management worldwide
2. International Association for Hydrogeologists: **https://iah.org/education/professionals/strategic-overview-series**. Strategic overviews aim to inform professionals and learners in a variety of sectors of key interactions with groundwater resources and hydrogeological science
3. Groundwater Governance—A Global Framework for Action: **http://www.groundwatergovernance.org/**. A multi-institution, global project designed to raise awareness of the importance of groundwater resources for many regions of the world and identify and promote best practices in groundwater governance as a way to achieve the sustainable management of groundwater resources
4. Global Groundwater Information System: **https://www.un-igrac.org/global-groundwater-information-system-ggis**. A web-based geographic information system that supports the storage, visualization, analysis, and sharing of groundwater data and information through map-based modules
5. WHYMAP: **https://www.whymap.org/whymap/EN/Home/whymap_node.html**. Mapping of groundwater resources of the world by BGR
6. International Shared Aquifer Resources Management program: **https://isarm.org/**. Serves as an umbrella for all transboundary aquifers projects and activities
7. GRAPHIC: **http://www.graphicnetwork.net/**. Dedicated to groundwater resources assessment under the pressures of humanity and climate change
8. Netherlands chapter of the International Association of Hydrogeologists: **https://www.hydrology.nl/iahpublications/201-groundwater-cartoons.html**. A series of cartoons on groundwater that can be used freely for presentations
9. Groundwater animation: **https://www.youtube.com/watch?v=uQRvN6MUajE**. A catchy video for presentations
10. License to Pump: **http://groundwater.stanford.edu/dashboard/index.html**. A dashboard for understanding groundwater permitting approaches across the Southwest United States by Water in the West, Stanford University