Global groundwater sustainability, resources and systems in the Anthropocene

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ABSTRACT (150 words plus 3 key points):

Groundwater is a crucial resource for current and future generations but 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, in order to inspire a pivot towards more sustainable pathways. We examine groundwater from three different but related perspectives of sustainability science, natural resource governance and management, and Earth Systems science. We propose that groundwater sustainability can be defined with a direct link with observable data, governance and management as well as the crucial functions and services of groundwater. An Earth System approach highlights the connections between groundwater and the rest of the hydrosphere, biosphere, atmosphere and lithosphere, and how these connections are impacting, or impacted by, groundwater pumping. 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 globalised world, that require broader analysis of interconnections between regions and knowledge transfer between regions.

1. Groundwater is depleted or contaminated in some regions and ubiquitously distributed which, importantly, makes it broadly accessible, but also slow and invisible and therefore challenging to govern and manage.

2. Groundwater is the largest store of unfrozen freshwater on Earth and is heterogeneously connected to a number of Earth System processes on different timescales.
3. 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?

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). Groundwater is crucial to environmental flows (T. Gleeson & Richter, 2018) and a diverse range of groundwater-dependent ecosystems (Kløve et al., 2011). Groundwater could be important to Agenda 2030 of the United Nations and its 17 Sustainable Development Goals (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 Sidebar 1).

Unfortunately, groundwater resources are threatened globally in a number of different regions where both quantity and quality issues are common (Aeschbach-Hertig & Gleeson, 2012; Bierkens & Wada, 2019; S. S. D. Foster & Chilton, 2003). 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 references in (Bierkens & Wada, 2019). 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 (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.

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 (Tóth, 1999). At or

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[1] slightly re-phrased from ‘man’ to ‘human’

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., 2019; Keune et al., ; Krakauer et al., 2014; Maxwell & Kollet, 2008; Meixner et al., 2016; Taylor et al., 2013) and contribute to streamflows and groundwater-dependent ecosystems (Batelaan et al., 2003; Boulton & Hancock, 2006; Kløve et al., 2011). Groundwater also impacts the oceans both through sea level (Petra Döll et al., 2014; Wada, 2016) as well as freshwater and solute inputs to the ocean (Moore, 2010; Sawyer et al., 2016; I.S. Zektser et al., 2007). Groundwater is also important in several geological processes 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; M. A. Person et al., 1996). Groundwater flow and chemistry is also related to biological activity subsurface and is 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 of 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 frameworks, the planetary boundaries (Rockström, Steffen, Noone, Persson, Chapin, Lambin, Lenton, Scheffer, Folke, Schellnhuber, Nykvist, de Wit, Hughes, van der Leeuw, Rodhe, Sörlin, et al., 2009; Steffen, Richardson, et al., 2015) although this has not been previously discussed at length (see Sidebar 2).

Why is examining groundwater at global scales useful?

Just a decade ago, groundwater was generally ignored in global hydrology models before global groundwater recharge was estimated for the first time (P. Döll & Fiedler, 2008). Seminal groundwater sustainability reviews highlighted that groundwater was critical to agriculture and people and locally overused or contaminated but that groundwater recharge, use, and quality was largely unknown for vast parts of the world, or at least not synthesized into a cohesive and consistent global perspective (S. S. D. Foster & Chilton, 2003; Giordano, 2009; Moench, 2004; Igor S. 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 (https://eartharxiv.org/zxyku/) allows us to: (1) understand and quantify the two-way interactions between groundwater and the rest of the hydrologic cycle, as well as the broader Earth System; (2) 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); (3) consistently and systematically analyze problems and solutions globally regardless of local context which could enable prioritization of regions or knowledge transfer between regions; and (4) 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 at both scales simultaneously. Groundwater depletion is considered a global problem owing to its widespread distribution and its potential consequences for water and food security and for sea-level rise (Aeschbach-Hertig & Gleeson, 2012; Leonard F. 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 (e.g., climate), groundwater storage, flow, and pumping are focused locally in aquifers that occur in specific locations. Groundwater flow and pumping in one location is likely to have a negligible effect on an aquifer across the world since the system is poorly mixed. Therefore, herein '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. (S. Foster et al., 12). Throughout this review, we focus on global aspects since this has been under-represented in groundwater sustainability literature, to support and complement regional efforts that we return to 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 a definition of groundwater sustainability which integrates of Earth Systems 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, atmosphere, and lithosphere. In Section 4, we discuss the benefits to considering a global and Earth Systems approach in context with regional scales and governance frameworks to contribute to groundwater sustainability efforts. In the Supplementary Information, we provide additional detail on the review scope: the time and space scales, how our review is different than other recent reviews on related topics and what is out of scope of this review. We began with the quote by Gandhi above to inspire ethical use of renewable groundwater resources.

Sidebar 1: Groundwater and the Sustainable Development Goals (SDGs)

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 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 a number of 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 only explicitly referenced once and a detailed analysis by Guppy et al was necessary to highlight the potential relationship 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 since 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).

Sidebar 2: 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, which together regulate the state of the Earth System (Rockström et al., 2009; Steffen et al., 2015) . Planetary boundaries have been widely 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. (https://eartharxiv.org/vfg6n/) argued that the current water planetary boundary, which is based on summing global streamflow and water use, should be replaced since 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 was 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 was argued to be 1) hydroecologic regulation, especially in relation to terrestrial or aquatic biosphere integrity and 2) storage in relation to sea level rise.

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, and popular to critique. The concept of sustainable development is generally 'meeting the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on the Environment and Development, 1987), which is a foundation of the widely - adoptedUN Sustainable Development Goals. The concept of sustainable development has been significantly critiqued as a contradictory oxymoron since economic development is often not sustainable (Robinson, 2004). Sustainability does not have a universal definition, but is generally considered a socio-ecological pursuit of a common ideal through the balancing of interconnected environment, 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 instead of being three balanced pillars, the sustainability Venn diagram looks more like ‘Mickey Mouse’ such that sustainability can be critiqued as ‘green-washing’ (Robinson, 2004). An important distinction is between weak sustainability, where all forms of capital (where capital can be natural, economic etc.) be substituted, and strong sustainability where some natural capital stocks are non-substitutable and thus must be maintained independently of the growth of other forms of capital (Pearce et al 1989).

Natural resources (see definition list) can be classified in different ways (Miller & Spoolman, 2011): 1) abiotic versus biotic; 2) renewable versus non-renewable; 3) ubiquitous versus localized distribution; 4) actual versus potential given current knowledge and technology; and 5) 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 it. 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 non-renewable (see section 2.2) that can generally be considered ubiquitous since the Earth is ubiquitously saturated at some depth (although the size, productivity and predictability of these resources varies incredibly). Herein, we generally focus on the actual resources given current knowledge and technology rather than hypothesizing 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 non-excludable (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.

Another useful way of describing groundwater as a resource is in comparison to surface water since surface water is a more visible and known resource. (Theesfeld, 2010) suggest other attributes of groundwater compared to surface water that are important in governance and management including that: 1) groundwater depletion or contamination can be irreversible; 2) there are often significant time lags between pumping and the impact of pumping; 3) groundwater system boundaries are often poorly constrained; 4) hydrogeologic uncertainty is often large; 5) pumping is often distributed broadly across regions; 6) data is often sparse and poor; and 7) information is asymmetrically held by organizations rather than individual users. Other useful descriptors of groundwater resources is invisible, slow-moving and distributed (Villholth & Conti, 2018) - we explore the implications of these characteristics below (Section 2.4). Numerous concepts have been proposed in physical groundwater hydrology to quantity groundwater sustainability of resources that we review next.

2.2 Limitations of previous concepts in physical groundwater hydrology

Here we review the limitations of several concepts which 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*** (Lee, C.H., 1915; Meizner, 1923; Theis, 1940). 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 been historically focussed 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 & 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. 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' (P. 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 y, known as the *mean renewal time*, Figure 1) (Bierkens & Wada, 2019; Margat et al., 2006). Both definitions are problematic, as using the rate of pre-pumping recharge propagates the 'water budget myth' (J. D. Bredehoeft, 2002) since it ignores the potential changes in recharge which may occur during ***capture*** as a result of pumping, and 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 also problematic for groundwater systems with long 'time to capture', since 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 also noted by (Bierkens & Wada, 2019; Margat et al., 2006), since it requires gross approximations regarding the average distribution of residence times within an aquifer; in reality all groundwater systems have complex groundwater residence time distributions, with some (often shallower) portions being more actively flushed with short turnover times, and some (often deeper) portions have 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.

Considering groundwater a dynamically, responsive system (Section 3), an improved definition of ***renewable groundwater*** is 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). This definition therefore integrates previous divergent definitions described above by considering both the dynamic balance of recharge and discharge fluxes, while also including changes in groundwater storage and recovery that may occur on human timescales. This implies that 1) no aquifer, volume of stored groundwater or flux of recharge can be considered 'renewable' without specifying a location, rate and timing of pumping; 2) the groundwater response time (Cuthbert et al., 2019) is important to consider since some lowering of groundwater levels is unavoidable during the 'time to capture' (J. Bredehoeft & Durbin, 2009). Such declines do not necessarily imply a situation of non-renewability unless the time to capture, and thus time to recover, is greater than a relevant human timescale; 3) the ***groundwater age*** 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 4) 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 rates while still leading to long term storage changes which would be considered as non-renewable.

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” (Leonard F. Konikow & Kendy, 2005) which is the definition generally followed in the regional-scale streamflow depletion and capture literature (P. M. Barlow & Leake, 2012; L. F. Konikow & Leake, 2014). Alternatively groundwater depletion is also more narrowly defined as the persistent decline in groundwater levels due to physically non-sustainable groundwater use (Bierkens & Wada, 2019) which is generally followed in the global hydrology literature (Petra Döll et al., 2014; Wada, 2016; Wada et al., 2012). Using 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, though we note that physical sustainability is just 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 is the ‘time to full capture’ (J. Bredehoeft & Durbin, 2009) may be very long - decades, centuries or even millennia - in many groundwater systems (Rousseau-Gueutin 2013, Cuthbert et al 2019a). Thus, while 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’ (J. Bredehoeft & Durbin, 2009) may lead to apparent ‘long term’ groundwater level declines which would not be considered as depletion using the second definition of groundwater depletion above. Thus, groundwater depletion is another variably defined term which can cause potential confusion unless it is understood that observed declines in groundwater level, over even multi-decadal timescales, are not sufficient evidence in themselves of physically non-sustainable 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 (1) the ratio of long term average annual pumping (Q) to the long term average annual recharge (R) i.e Q/R (2) 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 (3) the groundwater footprint (Tom Gleeson, Wada, et al., 2012) 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). While there seems to be broad spatial agreement in the results of these metrics (Tom Gleeson, Wada, et al., 2012; Richey et al., 2015; Wada & Heinrich, 2013) they also have a number of 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 stems from the difficulties in application of terminology derived from the management of other natural resources (e.g. energy, forestry); groundwater is a flowing dynamic and sometimes 'complex' (see below) system which makes applications of certain concepts and metrics unwieldy and sometimes non-intuitive. 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; Tom Gleeson, Alley, et al., 2012; Hiscock et al., 2002) have centered around the ambiguous balancing of environment, 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 'groundwater sustainability' is defining sustainability for a physical resource or stock. Purely physically-based definitions such as some definitions of safe yield or 'physical sustainability' as described above are too narrow since they do not include diverse social and environmental aspects. But in contrast, previous arguments of 'social' sustainability justifying groundwater mining (S. S. D. 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 (Tom Gleeson, Alley, et al., 2012) including 1) groundwater use always impacts the environment, because groundwater is derived from storage or capture; 2) the management of groundwater and surface water should be integrated, but often are not integrated; 3) decisions about groundwater use are value-driven; 4) a long term or multigenerational perspective is useful; and 5) 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** (see Definitions list) which is consistent with, but more easily operational than previous definitions. In this definition, the crucial functions and services provided by groundwater rest on two foundations: a physical-basis (dynamically stable groundwater levels, flows and quality as can be visualized in Figure 2) and equitable governance. The functions and services are derived from previous groundwater sustainability definitions and priorities (Alley & Leake, 2004; Council of Canadian Academies, 2009; Downing, 1998; Tom Gleeson, Alley, et al., 2012; 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 since it implies that part of groundwater natural capital stocks are non-substitutable, but it also allows for significant regional control through equitable governance and management and defining goals, targets and objectives. The physical-basis, governance and management and the 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 since groundwater (Figure 2b).

Since 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 non-sustainable pathways, namely managed aquifer depletion and strategic aquifer depletion (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 Texas (Tom Gleeson, Alley, et al., 2012). 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 (S. S. D. 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 a ~decadal scale) to strategically use groundwater (e.g. 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 since this is 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, p. 1). 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, In Press; Lautze et al., 2011; Pahl-Wostl et al., 2013). 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 (Food and Agriculture Organization of the United Nations et al., 2016).

Groundwater governance contains four key elements: (1) effective institutions that integrate stakeholders; (2) policies and capital that support local, regional, and global resource goals; (3) legal systems with the capacity to create and implement laws effectively; and (4) local knowledge, customary or cultural context, and scientific understanding of groundwater systems (Food and Agriculture Organization of the United Nations et al., 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). 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 paper, groundwater policy includes the actions used to guide decision making processes towards 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 non-compliance (Hornberger and Perrone, In Press). An effective legal system requires strong implementation processes such as measures to identify non-compliance. 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 (e.g., regulations, which have the force of law) or informal guidelines (e.g., policies, which do not have the force of law).

(4) To define good groundwater governance, local and regional information is critical. 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 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 amongst 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 groundwater framework directive (EU, 2000) shows 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 since this can provide a more holistic and larger-scale perspective, before returning in Section 4 to consider how groundwater groundwater sustainability could be complimented or expanded with an Earth System perspective.

3. Groundwater systems and the Earth System

3.1 What are complex systems and the Earth System?

Complex systems generally have boundaries which can be open and fuzzy as well as inputs, outputs and relationships between components. The Earth System is often considered a complex system (Rockström, Steffen, Noone, Persson, Chapin, Lambin, Lenton, Scheffer, Folke, Schellnhuber, Nykvist, de Wit, Hughes, van der Leeuw, Rodhe, Sörlin, 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. An important type of complex system in resilience literature are socio-ecological systems, which are an integrated system 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 socio-ecological system, can be considered a complex systems (Rica et al., 2018).

3.2 What are the crucial fluxes and characteristics of groundwater system?

Groundwater 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 is influenced principally by land cover, topography, soil type, geology and climate, but can also be affected by groundwater pumping (Figure 3). Diffuse recharge occurring in a spatially distributed manner over the land surface tends to dominate in more humid regions where precipitation 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 focussed (or indirect) recharge (Cuthbert, 2019; B.R. Scanlon et al., 2006). The input of recharge to the groundwater system sets up a hydraulic gradient under which groundwater flows naturally under gravity towards 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, in so far as this determines the pattern of hydraulic properties (e.g. permeability, drainable and compressible storage) of the sub-surface through which flow occurs. Where not complicated by such structures, flow systems 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 (known as aquitards) 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 (Tom Gleeson et al., 2011; Haitjema & Mitchell-Bruker, 2005). The groundwater response time is a measure of how long a groundwater system will take to equilibrate to new hydraulic boundary conditions (Cuthbert et al., 2019). Both the water table ratio and the groundwater response time help to characterize the distribution of hydraulic heads in groundwater systems. Other metrics, such a **groundwater age** and **residence time** (Bethke & Johnson, 2008; Phillips & Castro, 2003), can be used to characterize the time scales 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 groundwater response times) typically occurs much more rapidly than solute transport (which determine groundwater residence times and ages).

3.3 What are the crucial connections between groundwater and other components of the Earth System?

Groundwater is the largest store of liquid freshwater on Earth (Alley et al., 2002; Tom Gleeson et al., 2016). Despite this large volume of groundwater, the fluxes between groundwater and other compartments of the hydrologic cycle are relatively small compared to those on and above the Earth's surface.. While 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), regulation of temperature (Powers, 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 non-linear 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 rest of hydrosphere; atmosphere; and lithosphere, and how these connections are impacted by pumping (Figure 3).

Biosphere and rest of 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 (Figure 3)(T. Gleeson & Richter, 2018; Mukherjee et al., 2018). This may be due to reductions in flow rates and/or variations in water chemistry or temperature. Where groundwater discharges to lakes, wetlands, rivers and streams, it provides a stabilising 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 which 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).

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% (https://eartharxiv.org/sw8r4). 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, p. 20). 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 these areas, which has led to seawater intrusion into coastal aquifers in many regions (P. 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).

Atmosphere: Interactions between the atmosphere and groundwater occur variably at locations of recharge and discharge, and can be characterised as having either unidirectional or bidirectional modes of interaction (Figure 3e). These modes can be usefully classified using the WTR. Values of WTR>1 correlate globally with shallow water table depths and indicate predominantly bidirectional mode of climate-groundwater interaction i.e. 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 land-atmosphere energy exchanges can be limited by the presence of shallow groundwater (Maxwell & Condon, 2016; Maxwell & Kollet, 2008). In contrast, in areas with WTR<1, are indicative of unidirectional interaction whereby the land surface is decoupled from the groundwater to such as 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.

Lithosphere: Groundwater is known to be key driver of weathering in the subsurface. Weathering profile are sensitive to the position of the water table and groundwater recharge rates discharge(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; Jennifer C. 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 hydrography 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 higher deep groundwater can often contain 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) and by the energy industry (Jennifer C. McIntosh & Ferguson, 2019; Bridget R. Scanlon et al., 2017) 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 increasingly connection driven by global trade, culture and information exchange (Steffen, Broadgate, et al., 2015) where 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 simultaneously view groundwater 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 perspective is crucial to groundwater sustainability, and often requires that regional perspective be integrated in a global framework; we include a description of groundwater within a global sustainability framework, the UN Sustainable Development Goals. 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 entitled 'the world in 2050' highlights how goals could be set for meeting the Sustainable Development Goals (SDGs) by 2030 while staying within the planetary boundaries by mid-century (TWI2050, 2018). Each region would have a different trajectory to meet these goals because of these regional differences.

Human and regional perspectives on groundwater sustainability

Groundwater sustainability necessitates incorporating human perspective into governing and managing the physical resource (Alley & Leake, 2004; Tom Gleeson, Alley, et al., 2012; 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 does 'dynamically stable groundwater levels' mean for a particular aquifer?), 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 (Sidebar 3).

Since this is a review of global groundwater sustainability, we use how groundwater relates to Agenda 2030 of the United Nations and its 17 Sustainable Development Goals (SDGs; Sidebar 1), to guide a discussion of regional differences. Considering groundwater in the SGDs 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 in a significant concern - in these regions, logically, 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 and groundwater resources are not significantly developed and groundwater depletion is not a concern - in these regions sustainably increasing groundwater use in order to contribute to achieving the SDGs may be important. Groundwater can be a more distributed and resilient water source compared to surface water so that groundwater could continue to enable significant socio-economic 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 SDGs fulfillment and groundwater sustainability as well as between the conflicting relationships within the SDGs (Sidebar 1). In the future, SDG fulfillment could be considered a second tier of groundwater sustainability analysis and metrics in addition to the definition in Section 2.2.

Earth system perspectives on groundwater sustainability

Although the connectedness of the Earth's System provides for an intimidating start, it also provides for 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, atmosphere, and lithosphere. While there have been efforts to include groundwater hydrology into Earth Systems 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 Systems framework will require looking from pumped portions of aquifers outwards, rather than simply looking at the portions of groundwater systems that are strongly connected to other of the Earth Systems under natural conditions. The Earth System perspective on groundwater sustainability and resources is likely more useful and interesting for more holistically examining cumulative impacts of pumping on large scales. This perspective is less likely to be useful or 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 like Ferguson & Gleeson (2012) who compared the impact of groundwater pumping versus sea level rise on saltwater intrusion in coastal aquifers. Additionally, this approach encourages a broader 'systems' thinking on groundwater sustainability and resources through the connections between groundwater and the biosphere and rest of 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 (Sidebar 2), 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.

Concluding Remarks

In sum, we urgently need a pivot towards more sustainable groundwater 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 which 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 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.

Sidebar 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 5c) starts with defining a desirable future and then works backwards to identify policies and programs that will connect that future to the present. Conjunctive management of groundwater and surface water is also paramount since 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 being used increasingly in places where localized information is not feasible to collect.

3) Green to grey infrastructure. Grey 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). Grey infrastructure such has managed aquifer recharge has long been practiced (O’Hare et al., 1986); when paired with green infrastructure, nature-based solutions can emphasis climate change adaptation or water quality.

Summary Points list (max 8)

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 make it accessible to rural or disadvantaged communities but challenging to govern and manage. Groundwater governance is often fragmented, with vast differences amongst 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 a number of Earth System processes on different timescales.

6. An Earth System approach highlights the connections between groundwater and rest of 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 list (max 8; must be complete sentences)

1. **Groundwater quality**: Data synthesis, analysis and modeling of patterns, time and space scales, drivers of global groundwater quality and integrating groundwater quality and quantity is needed, including point source, non-point source and novel pollutants.
2. **Groundwater sustainability simulators and decision-support tools**: We need to develop a holistic quantitative analysis and modeling framework that is useful for interdisciplinary groundwater sustainability goals . This framework may include elements or linkages of agent-based models (Castilla-Rho et al., 2017), hydrologic models of coupled groundwater-surface-atmosphere (de Graaf et al., 2017), economic models (Kahil et al., 2018), land use models as well as an accessible user-interface for water managers to run scenarios and trade-off analysis.
3. **Groundwater sustainability as Grand Challenge and exemplar of Earth System sustainability:** 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 since groundwater like other parts of the Earth System have a wide range of residence times, distributed resource, complex and heterogeneous management and governance?
4. **Groundwater in global sustainability frameworks**: The role and importance of groundwater in the UN Sustainable Development Goals as well as the planetary boundaries needs clarifying and resolving in order to work towards defining a safe and sustainable operating space for groundwater. This research may integrate the role of groundwater in environmental flows (T. Gleeson & Richter, 2018) and/or ecosystem services (Griebler & Avramov, 2015).
5. **Groundwater and resilience**: the resilience of socio-ecological systems such as groundwater in irrigated agricultural watersheds is under-researched and appreciated. Applying a resilience lens to groundwater could involve resilience across different time scales (see https://www.biorxiv.org/content/10.1101/549873v1).
6. **Law of the Hidden Sea or groundwater in the global commons**: Although subsurface rights are defined in many regions, exploring a global ethical framework for a 'Law of the Hidden Sea' or more generally how, or if, groundwater should be considered part of the global commons could be fruitful (Lopez-Gunn & Jarvis, 2009).
7. **Groundwater and the good Anthropocene**: 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. **Global groundwater governance**: Groundwater governance to date has always been at local to national scales except for transboundary aquifers and the European Union groundwater directive and groundwater 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.

OPTIONAL ELEMENTS - not included in word count

Terms and Definitions list

Aquifer: geological formations that contain water and is able to transmit significant quantities of water under ordinary hydraulic gradient (Hiscock & Bense, 2014)

Capture: increased recharge and decreased discharge due to pumping (J. Bredehoeft & Durbin, 2009; L. F. Konikow & Leake, 2014; Lohman, 1972)

Complex systems: 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, which are often non-linear and nested, and can have memory, feedbacks and emergent behavior (Thurner et al., 2018).

Discharge: the flux of groundwater from the subsurface to above ground, either in terrestrial or aquatic environments. Often in hydrology, streamflow is also confusingly called ‘discharge’ but herein we use the term streamflow.

Dynamically stable: 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 non-stationary Anthropocene.

Earth System: complex system composed of different interacting components such as the hydrosphere, lithosphere, atmosphere and biosphere. Note that we follow Steffen et al (Steffen et al., 2006) in capitalizing Earth System to emphasise that the Earth functions as a single, complex, interacting system.

Environmental flows: the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being (Arthington et al., 2018).

Groundwater age: time elapsed since a particular groundwater molecule was recharged (Kazemi et al., 2006). See Bierkens & Wada (2019) for definitions of modern groundwater and fossil groundwater.

Groundwater depletion: Two definitions are common in the literature: 1) broadly defined as *any* groundwater level decline due to “the inevitable and natural consequence of withdrawing water from an aquifer” (Konikow & Kendy 2005), or 2) more narrowly defined as the *persistent, multi-annual* decline in groundwater levels due to pumping (Bierkens & Wada 2019). Herein we use the latter definition since it is more commonly used in the global-scale literature.

Groundwater governance: the “overarching framework of groundwater 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).

Groundwater storage loss during capture: Groundwater storage loss that is inevitable and necessary in order to pump groundwater from a well by inducing a hydraulic gradient towards the well. This is sometimes included in definitions of ‘groundwater depletion’ (L. F. Konikow & Leake, 2014).

Groundwater sustainability: maintaining dynamically stable groundwater levels, flows and quality with equitable, effective and long-term governance and management to sustain water, food and energy security, environmental flows and groundwater-dependent ecosystems, infrastructure, social well being and local economies for current and future generations.

Groundwater Management: day-to-day activities associated with meeting the groundwater resource goals set under the groundwater governance framework.

Natural resources: ‘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, since groundwater is a natural resource.

Planetary boundaries: scientifically-defined limits to the human perturbation of global environmental processes (such as climate change or water use) that regulate the stability of the planet (Rockström, Steffen, Noone, Persson, Chapin, Lambin, Lenton, Scheffer, Folke, Schellnhuber, Nykvist, de Wit, Hughes, van der Leeuw, Rodhe, Sorlin, et al., 2009; Steffen, Richardson, et al., 2015).

Pumping: 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 since this is plain language.

Recharge: variably defined as “the downward flow of water reaching the water table, adding to groundwater storage” (Healy, 2010) or “water that reaches an aquifer from any direction (down, up or laterally)” (Lerner 1997 cited by Scanlon et al 2002). Recharge can be anthropogenically augmented by a variety of means (including as irrigation return flows) or ‘artificial/managed recharge’ (Dillon et al., 2019).

Renewable groundwater: several definitions exist (see text) but here we define this as any groundwater that can be dynamically captured (see definition of capture) during pumping that leads to new dynamically stable (see definition) groundwater levels on human timescales (e.g. ~100 years).

Residence time: travel time from recharge to discharge (Kazemi et al., 2006). 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).

Safe yield: the amount of rejected recharge plus the fraction of natural discharge it is feasible to utilize (Theis, 1940). See Section 2.3 for references to other definitions.

Socio-ecological systems: integrated systems of ecosystems and human society with reciprocal feedback and interdependence (Folke et al., 2010).

Related Resources list (websites, articles, animations)

1. International Groundwater Resources Assessment Centre (IGRAC) facilitates and promotes international sharing of information and knowledge required for sustainable groundwater resources development and management worldwide.
2. Strategic overviews by International Association for Hydrogeologists (IAH) aims 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’ was a multi-institution, global project was 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 (GGIS) is a web-based Geographic Information System, which supports the storage, visualisation, analysis and sharing of groundwater data and information through map-based modules.
5. WHYMAP is mapping of groundwater resources of the world by BGR
6. ISARM (International Shared Aquifer Resources Management) Programme serves as umbrella for all transboundary aquifers projects and activities

7. GRAPHIC is dedicated to Groundwater Resources Assessment under the Pressures of Humanity and Climate Change.
8. The Netherlands Chapter of IAH has produced a series of cartoons on groundwater that can be used freely for presentations; .
9. Groundwater animation which is a catchy video for presentations.
10. 'License to pump' is a dashboard for understanding groundwater permitting approaches across the Southwest United States by Water in the West, Stanford University.

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Suggested Reference Annotations (max 10)

1. Bierkens and Wada review -
2. Alley - Safe yield to sustainability
3. Alley - Flow and storage in groundwater systems
4. Theis 1940
5. Bredehoeft 2002
6. Aeschbach & Gleeson 2012?
7. Castillo-Rho et al 2017
8. Villholth book
9. (Margat & Van der Gun, 2013)

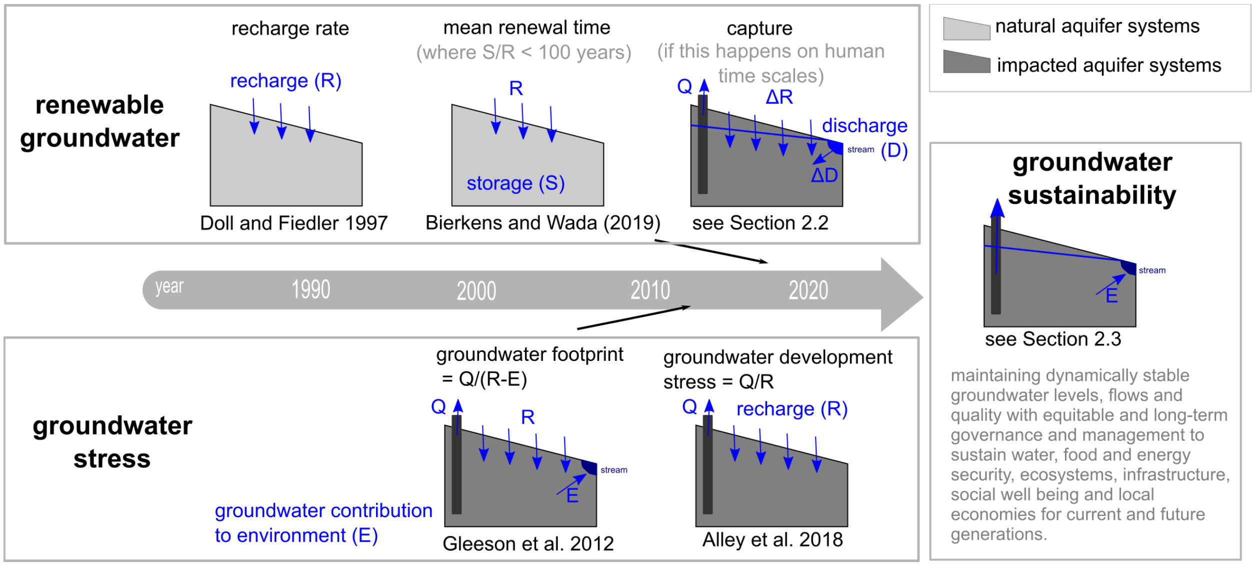

Figure 1. The evolution of key terms such as renewable groundwater, groundwater stress and groundwater sustainability. Note the blue 'water table' line is not included in most of the diagrams, since it is not explicitly considered in definitions of renewable groundwater or groundwater stress. **[small figure]**

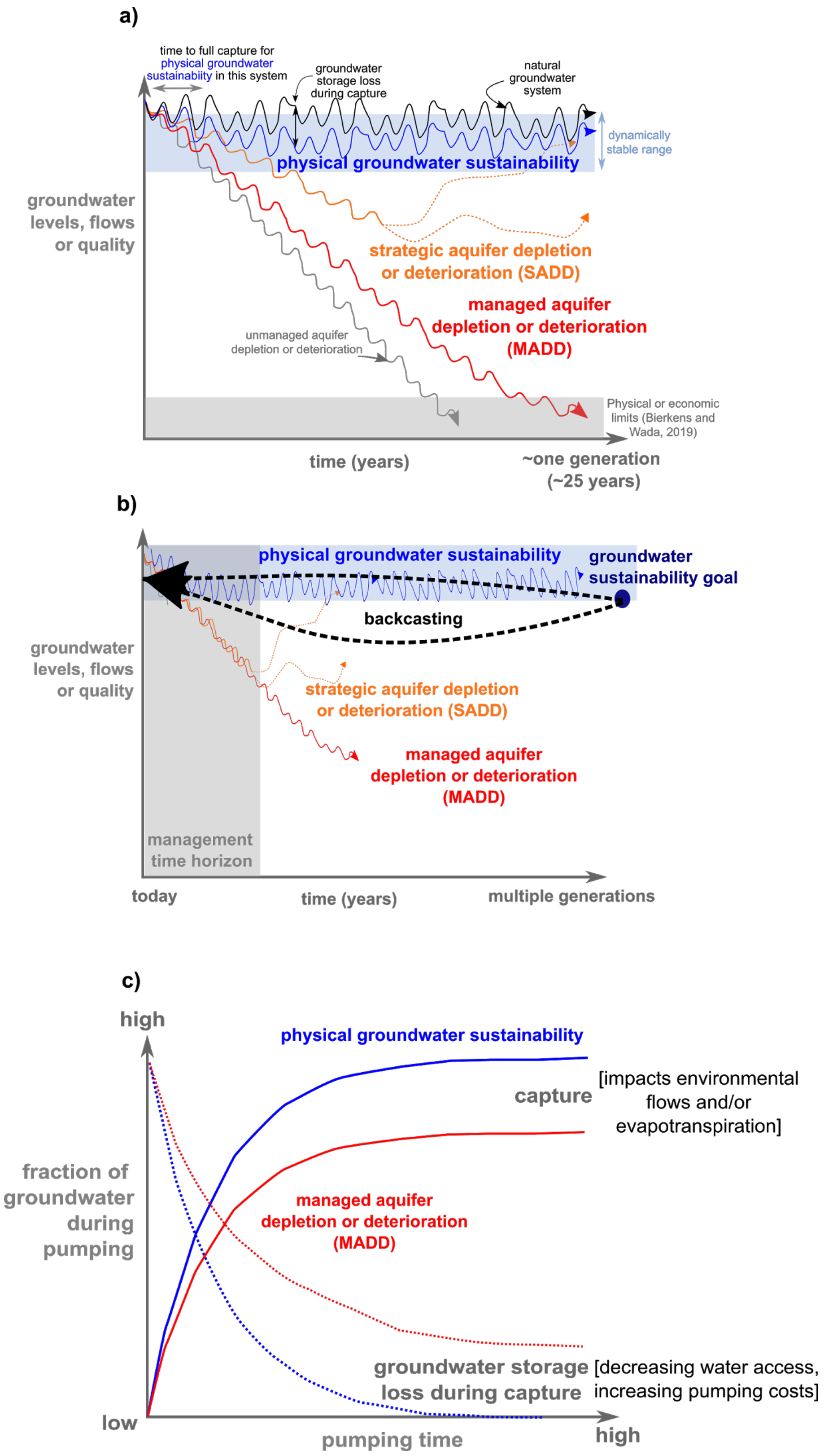

Figure 2. Groundwater sustainability. a) physical groundwater sustainability. The blue 'physical groundwater sustainability' line deviates from the black 'natural groundwater system' line for some time until 'time to full capture'. This scenario assumes no change in long term groundwater recharge. b) Setting long-term groundwater sustainability goals and which can then using backcasting to determine which actions are necessary in the management time horizon. Note that the time scales in b) is longer than the time scale in a) (modified from Gleeson et al, 2012. c) the source of groundwater to wells during pumping contrasting physical groundwater sustainability and managed aquifer depletion (modified from Konikow & Leake, 2014) **[large figure]**

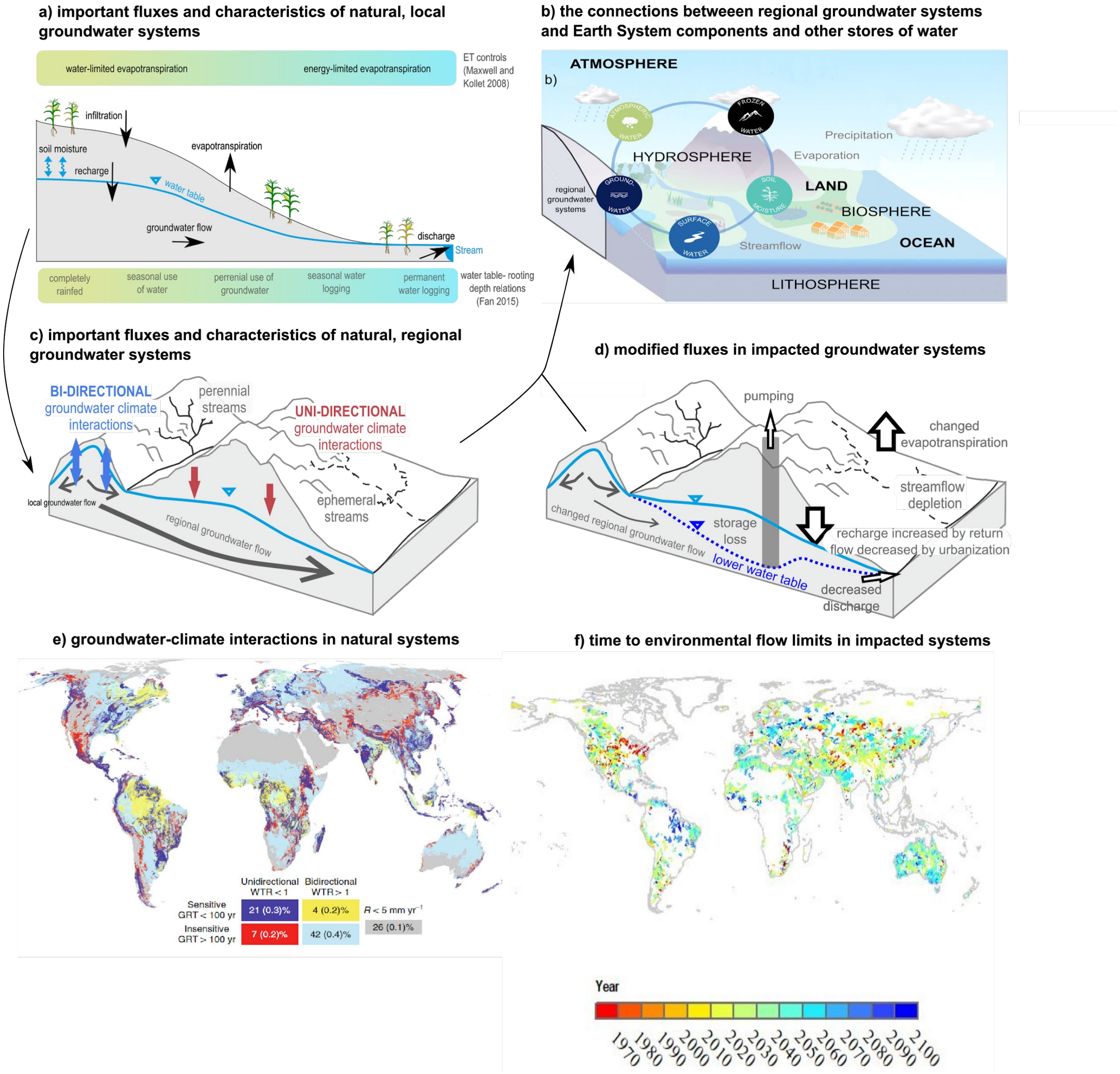

Figure 3. Natural and impacted groundwater systems and then within earth system. a) important fluxes for local groundwater systems not including focused recharge or preferential flow (< ~10 km length scale; modified from Fan 2015 and Maxwell and Kollet 2008). b) the connections between groundwater and 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 (modified from https://eartharxiv.org/vfg6n/ and Oki and Kanae 2006). 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; modified from Cuthbert et al 2019) and d) modified fluxes in impacted groundwater systems (modified from Aeschbach-Hertig and Gleeson 2012). e) Groundwater is connected to various earth systems such as climate (see Cuthbert et al. 2019 for

description of terms). Groundwater pumping leads to streamflow depletion which impacts which impacts environmental flows on different time scales (de Graaf et al in press).**[large figure]**

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Supplementary Information

Further detail on scope of review:

The Anthropocene is time frame is consistent with ‘modern groundwater’ (Tom Gleeson et al., 2016) but the reason for focusing on the Anthropocene is to unravel groundwater sustainability when it is most challenged rather than focus on groundwater of a certain age. We do not discuss groundwater through deep time (Marshak and Bethke, 1990; Hanor, 1994; Holland et al., 2013; Ferguson et al., 2018) or even during the last glacial cycle (Lemieux et al., 2008; J. C. McIntosh et al., 2012; M. 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., 2019). Similarly, we focus on global groundwater processes, both natural and impacted by humans, so we primarily consider regional scale (10’s to 100’s km) 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 since this is covered in hydrogeology textbooks (Fetter, 2001; Hiscock, 2005; Schwartz & Zhang, 2003). All wells shown in figures illustrate pumping from the system of general rather than a specific well.

This review is different than other recent reviews on related topics (Aeschbach-Hertig & Gleeson, 2012; Bierkens & Wada, 2019; Wada, 2016)(Dalin et al 2019). Aeschbach-Hertig & Gleeson (2012) synthesized groundwater depletion and suggested the groundwater depletion be considered from diverse perspectives of hydrology, economics and policy studies. Wada (2016) reviewed how groundwater depletion is modeled at regional- to global-scale while Dalin et al (2019) focuses on how unsustainable groundwater use is related to global food production and international trade through virtual water. Bierkens and Wada (2019) review the drivers and processes related to groundwater depletion, redefining non-renewable groundwater as well as the physical, environmental and economic processes and limits of non-renewable groundwater. In general, we more holistically consider groundwater from multiple perspectives of sustainability, resources and systems, and 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 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 (S. Foster & MacDonald, 2014), groundwater economics (Bierkens & Wada, 2019), food security (Dalin et al 2019 REF), virtual water (D'Odorico et al., 2019) and the food-energy-water nexus (Endo et al., 2015). We include groundwater quality as part of groundwater sustainability and acknowledge that groundwater quality is an important aspect of groundwater in the Earth System; (S. S. D. 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 that we do not address but return to in the 'Future topics'. We discuss the role the ecological role of groundwater at or above the surface but not subsurface groundwater ecosystems since this has 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 (Bridget R. 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 in early human evolution or early history (Cuthbert et al., 2017; Mays, 2013).