Issue Paper/

Groundwater in complex adaptive social-ecological systems

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Conflict of interest: None

Key words: Groundwater sustainability, Social-ecological system, Complex adaptive system, Groundwater-connected system

Article Impact Statement: A call to embrace complexity and interdisciplinarity in groundwater sustainability work through a social-ecological systems approach.

Abstract

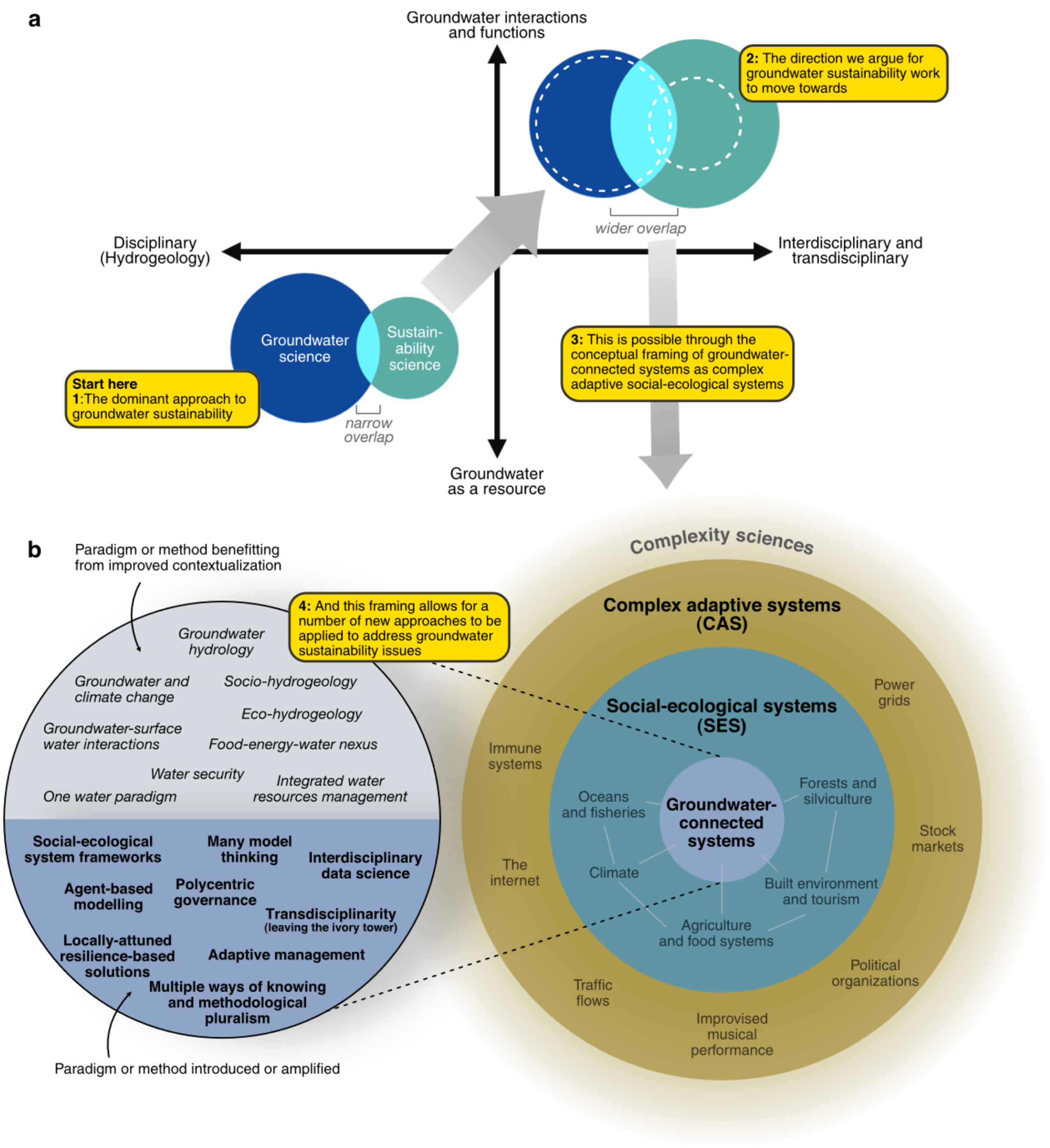
Groundwater is embedded in social and ecological systems but the complexity of these interactions is not well represented in conventional approaches to study and promote groundwater sustainability. We argue an important shift is necessary in groundwater sustainability thinking: towards prioritizing the functions of groundwater, and the services that make it a critical resource, and away from focussing on the resource in isolation. We articulate a new perspective for groundwater sustainability based around the concept of groundwater-connected systems—any system with dynamic relationships with groundwater, which can include ecological, social, and Earth systems. We draw from the emerging field of sustainability science and consider groundwater-connected systems to be specific forms of both social-ecological systems and complex adaptive systems. We argue this interdisciplinary systems-based perspective is necessary to connect existing research domains and paradigms, and provides additional concepts and tools from the established literatures of social-ecological systems and complex adaptive systems to improve how we study and manage groundwater-connected systems for resilience and sustainability. We provide a theoretical foundation for this perspective and discuss its practical implications which span data collection initiatives, scientific investigations, governance, and management approaches. Amidst calls for innovation in the groundwater field, we argue that embracing the groundwater-connected system perspective can underpin a methodologically pluralistic, interdisciplinary, community-wide, and bold new wave of groundwater research to better understand and promote groundwater sustainability in the complex systems groundwater is embedded within.

A systems perspective for groundwater sustainability

Groundwater sustainability can be understood as maintaining the state of groundwater such that it continues to provide long term and widespread benefits to human well-being while preserving its ecological and Earth system functions. This description may not appear novel but it does reflect an important shift in approaching groundwater sustainability: prioritizing the *functions* and *interactions* of groundwater, and the services that make it a critical resource, instead of focussing on the resource itself. There has been great progress in developing awareness and a better understanding of groundwater interactions with social (Re 2015), ecological (Cantonati et al. 2020), and Earth (Gleeson et al. 2020) system processes, as well as the dependency of groundwater itself on these processes. Combined, these interactions affirm and elevate the importance of using and managing groundwater on the basis of its core functions and services for long-term sustainability and resilience of integrated hydrological, social, ecological, and Earth systems. Yet, despite an accelerating research agenda on groundwater sustainability as a topic (Elshall et al. 2020), integrated systems, function-oriented, and interdisciplinary approaches to groundwater sustainability are underrepresented in the literature. This underrepresentation is possibly due to the complex and uncomfortable nature of this perspective: much more than hydrogeology expertise is required, though it remains foundational and necessary.

In this paper, we elucidate on, advocate for, and describe the implications of this new framing. We first describe the complexity and breadth of challenges that characterize the groundwater sustainability problem space, which continues to expand as groundwater interactions with diverse systems and processes continue to be revealed. We then highlight core elements of sustainability science whose benefits have yet to be realized within groundwater sustainability topics. We proceed to articulate our framing of groundwater as a resource embedded in complex adaptive social-ecological systems. Lastly, we discuss the implications of this perspective on data collection, scientific investigations, governance, and management. Our motivation is not to refine perceptions of the broad and severe impacts of groundwater misuse, but rather to highlight how a wider, more complex, interdisciplinary, and systems approach to groundwater makes available a suite of new (or existing but underutilized) concepts and method to promote transformations towards sustainability and resilience in complex groundwater-connected systems.

This perspective entails moving the field of groundwater sustainability from a predominantly disciplinary pursuit—focussed on groundwater as an isolated resource and one dominated by hydrogeologists' perspectives, methods, and paradigms—to an interdisciplinary pursuit focussed on preserving core functions of groundwater relationships within larger, interconnected social-ecological systems through interdisciplinary and transdisciplinary methods and collaborations (Figure 1). The framing and approaches we present are not a criticism or a call to replace existing research methods or programs tackling issues pertaining to groundwater sustainability. Rather, we offer this framing as a more expansive, overarching perspective that can complement existing approaches and paradigms, such as socio-hydrology, integrated water resources management, nature-based solutions, and the food-energy-water nexus (Gain et al. 2021). We will start by summarizing key concepts already established within the sustainability science field but that may be new to groundwater researchers and practitioners. These concepts can help tie together the many perspectives, methods, efforts, and skill sets required to promote groundwater sustainability in the Anthropocene.



Start here
1:The dominant approach to groundwater sustainability

2: The direction we argue for groundwater sustainability work to move towards

3: This is possible through the conceptual framing of groundwater-connected systems as complex adaptive social-ecological systems

4: And this framing allows for a number of new approaches to be applied to address groundwater sustainability issues

Figure 1. Framing groundwater sustainability as an integration of groundwater science and sustainability science, and viewing groundwater resources through the lens of groundwater-connected systems. (a) We argue for approaches targeting groundwater sustainability to move from disciplinary pursuits focusing on groundwater as a resource to inter- and transdisciplinary collaborations that focus on understanding and maintaining groundwater interactions and functions. (b) This new perspective is enabled by focusing on groundwater-connected systems and evaluating these systems as social-ecological systems and complex adaptive systems. Doing

so introduces or amplifies new methods and paradigms for data, research, governance, and management. To support interpretation of this figure, consult the yellow text boxes in sequential order.

Groundwater sustainability as a wicked, undisciplinary pursuit

Groundwater sustainability is a wicked problem (Lönngren and van Poeck 2021): those with no single solution, where nontrivial, complex system dynamics formed by interactions across social, economic, and environmental dimensions can turn well-intended interventions into undesirable consequences. Wicked problems are not easily ‘solved’, with no finite set of potential solution strategies or clear stopping criteria, and thus require sustained efforts to manage or mitigate their consequences (Crowley and Head 2017). Drivers of groundwater depletion and misuse are also complex and diverse, and the challenge of steering groundwater systems on pathways towards sustainability is, as a result, well reflected in the literature (e.g. see Aeschbach-Hertig and Gleeson 2012; Ostrom 1993; Zellner 2008; Zwarteveen et al. 2021). Impacts of groundwater misuse are also widely discussed in the literature, including a number of recent review articles (e.g. Bierkens and Wada 2019; Gleeson et al. 2020; Lall et al. 2020).

Important groundwater and groundwater-connected processes occur across a wide range of spatial and temporal scales. These include biophysical (i.e. physical and ecological) and social (including technological and economic) systems and processes, and span well-head (local), to catchment, aquifer, and transboundary domains, to the global scale, and across seasonal to century and longer time ranges (Figure 2). Interactions between these processes of dramatically different spatial and temporal scales are at the root of the wicked nature of groundwater sustainability challenges.

Given the diversity and interconnectedness of drivers of hydrogeological processes, the relevant scientific disciplines currently contributing towards critical insights to characterize and remedy groundwater challenges are also numerous. We may readily identify hydrology, geology, climatology, ecology, sociology, economics, and policy science domains. Though this list is far from comprehensive, it underscores the need for greater interdisciplinarity in groundwater research. Furthermore, transdisciplinary work in groundwater sustainability is necessary for solutions to address the core needs of stakeholders and promote social and ecological well-being through place-based strategies (Re 2021; Castilla-Rho et al. 2020). These transdisciplinary interactions between academics and stakeholders can create synergistic interactions across knowledge systems and worldviews. Yet, as we argue here, making such interactions fruitful demands entirely different skill sets to those used in traditional, discipline-specific groundwater research when can benefit from a reframed conceptualization and approach to groundwater sustainability research.

Groundwater sustainability should be understood as a problem-oriented domain. Such problem-oriented sustainability work has been described as undisciplinary, defined as: “problem-based, integrative, interactive, emergent, [and] reflexive science, which involves strong forms of collaboration and partnership” (Robinson 2008; Haider et al. 2018). We note, however, that existing work framed in this fashion has predominantly focussed on resources and sustainability issues other than groundwater. We find it compelling to contrast this understanding of “undisciplinary” science with H. Schwartz’ *Groundwater* editorial “Zombie-Science and Beyond” (2013) where stagnation within hydrogeological research was questioned with a call for innovation through non-traditional approaches. We argue that embracing such an “undisciplinary” approach to addressing the wicked problems associated with groundwater sustainability can serve as one key area for growth in the groundwater field, with marked benefits for groundwater sustainability efforts that are becoming more urgent (Famiglietti 2014).

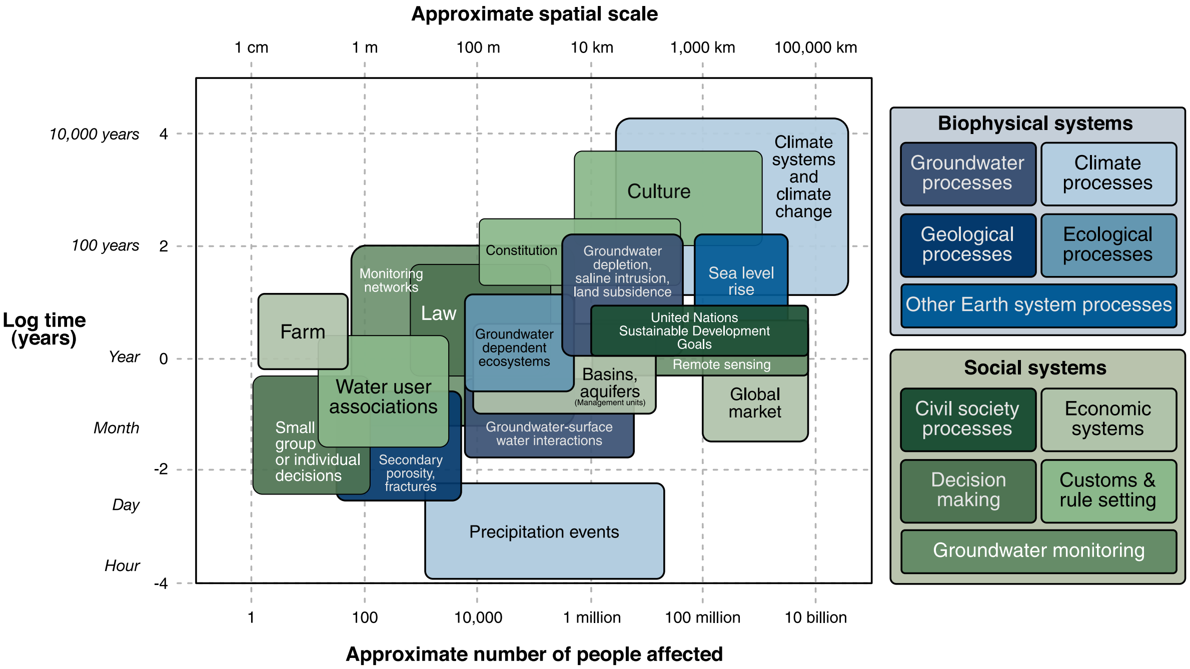


Figure 2. Spatial, temporal, and social scales of biophysical and social processes of groundwater-connected systems. The processes shown are meant to be illustrative of the diversity of processes across scales rather than being exhaustive.

Box 1: Definitions of key terminology, as used in this paper.

Complex adaptive system: A system of interacting components which are "defined more by the interactions among their constituent components than by the components themselves" (Preiser et al. 2018). Complex adaptive systems can take many forms, but are generically comprised of relational networks, which have adaptive capacities, possess dynamic processes, are open systems with context-dependent and emergent behaviour (Preiser et al. 2018).

Social-ecological system: An integrated system formed by interactions between social and biophysical systems (Berkes and Folke 1998). Social-ecological systems can possess complex system attributes including thresholds, feedbacks, non-linear processes, path dependent behaviour, and are understood to exist within the context of external social, economic, and political settings and in relation to ecosystem processes (Ostrom 2009). Social-ecological systems are specific forms of complex adaptive systems.

Groundwater-connected system: Any system that has a dynamic relationship(s) with groundwater. Groundwater-connected systems thus encompass interactions and relationships identified through both groundwater-based socio-hydrology and eco-hydrology literature. Borrowing from the complex adaptive system literature, the groundwater-connected system perspective focuses not on evaluating the hydrogeological system itself, but rather on understanding the properties and dynamics of the interactions between groundwater and connected systems. Groundwater-connected systems are specific forms of social-ecological systems.

Interfacing sustainability science with groundwater

Sustainability science, as a discipline, has emerged in the last two decades in response to the myriad ways humans are challenging physical and ecological limits across local to global scales (Kates 2011). Sustainability-focused groundwater research is increasingly being conducted (Elshall et al. 2020) and overlap in these studies with core sustainability science concepts (such as proposing groundwater sustainability definitions, footprinting analysis, and interdisciplinary problem-oriented collaborations) is natural and already occurring (Gleeson et al. 2020; Barthel and Seidl 2017). However, explicitly tethering core sustainability science concepts, theories, frameworks, and approaches to the groundwater sustainability literature and discourse can only assist in providing additional tools to address groundwater sustainability challenges by tapping into a wider, deeper, and more developed literature.

Sustainability science is framed as a consilient, problem-based, and undisciplinary domain (Ayres et al. 2001; Kates 2011; Haider et al. 2018; Jerneck et al. 2011). Its consilient nature emphasizes the collaboration needed between disciplines to support stronger, more substantiated outcomes that resolve concepts and theories across the concerned disciplines. The sustainability science literature is large, diverse, and pluralistic (Bettencourt and Kaur 2011) and there is no unifying theory that underpins the discipline. Core facets of sustainability science include the philosophical and ethical foundations of sustainability definitions, the identification of goals and targets that indicate progress towards sustainable development, the development of frameworks, and the application of these frameworks to develop theories and models (McGinnis and Ostrom 2014) to assess systems whose sustainability is of concern.

As resource-based sustainability issues are fundamentally rooted at the interface of human and environmental systems, a central concept that permeates the sustainability science discourse is that of social-ecological systems (de Vos et al. 2019). Social-ecological systems (Box 1) offer a way of viewing human-environmental interactions as a single, interconnected system with physical, ecological, and social components (Berkes and Folke 1998; Chapin et al. 2009). Naturally, there has been significant uptake of the social-ecological system concept across sustainability science, and myriad frameworks have emerged to study social-ecological systems (Binder et al. 2013). Social-ecological systems are also understood to be complex adaptive systems (Box 1; Preiser et al. 2018). This framing locates sustainability science as a complexity discipline, characterized by systems with dynamic processes, deep uncertainty, emergent and context-dependent behaviour.

We note that sustainability-focused groundwater research is rarely approached from an explicit social-ecological perspective (though there are exceptions, e.g.: Delgado-Serrano and Borrego-Marin 2020; Bouchet et al. 2019; Barreteau et al. 2016; Carpenter et al. 2015), and to the best of our knowledge no foundational literature explicitly discusses the varied advantages of adopting this perspective. However, groundwater sustainability research has become increasingly interdisciplinary, as evidenced by the emergence of socio-hydrology (Sivapalan et al. 2012), socio-hydrogeology (Re 2015), and eco-hydrogeology (Cantonati et al. 2020) disciplines. It has been argued that socio-hydrology itself corresponds closely with social-ecological system approaches (Madani and Shafiee-Jood 2020), however we suggest that the more expansive concept of social-ecological systems is better equipped to include interactions with and between ecological and Earth systems processes that may be underemphasized in socio-hydrological studies. Furthermore, as there has yet to be widespread uptake of groundwater topics in the socio-hydrological literature (see Troy et al. 2015), there remains significant room for growth and application of socio-hydrological research that expands to accommodate a social-ecological system perspective.

In order to advance this social-ecological perspective in groundwater sustainability research, a conceptual shift that focuses on groundwater-connected systems (Box 1) rather than on groundwater resources in isolation is necessary. This shift is consistent with recent calls to adopt a “One Water” paradigm (Villholth 2021), but elaborates with greater specificity about groundwater processes and connections within this general perspective. Approaching groundwater-connected systems as complex adaptive social-ecological systems can have profound implications on the approach of data collection and scientific investigations that can provide unique and important insights to better guide governance and management. Furthermore, the social-ecological system perspective (itself developed through inter- and transdisciplinary work) can prove useful in facilitating collaborations and communication between the many research domains across the groundwater sustainability problem space. Our view is that aligning diverse inputs through a common paradigm and its associated language can support the type of undisciplinary collaborations required to achieve diverse and multi-faceted groundwater-based and groundwater-related sustainability goals (Guppy et al. 2018; Di Baldassarre et al. 2019).

Groundwater-connected systems as complex adaptive social-ecological systems

Through the groundwater-focused socio-hydrology and eco-hydrogeology literature, human-groundwater and ecological-groundwater connections are becoming more apparent. Social and ecological systems, and together as social-ecological systems, have been identified and studied as complex adaptive systems (Levin 2005; Berkes and Folke 1998; Levin et al. 2013; Preiser et al. 2018). Because groundwater is embedded in social and ecological systems, we can lean on this existing literature framing social and ecological systems as complex adaptive systems to argue that groundwater should also be viewed as such. However, there is scant evidence that this perspective has gained attention or traction in the traditional groundwater hydrology research community to date. Furthermore, noting that ecological and social processes themselves form coupled systems, a more encompassing approach that considers the interactions between these systems and the underlying physical environment, including Earth system processes, is warranted. These premises combine to form the basis for our thesis: ***that it is advantageous for groundwater sustainability efforts to focus on groundwater-connected systems, rather than groundwater resources, and to consider these groundwater-connected systems as complex***

adaptive social-ecological systems. To connect theoretical foundations with empirical evidence to support this perspective, we map (see Figure 3) components, attributes, and dynamics of groundwater-connected systems to fundamental principles and elements of social-ecological systems (Figure 3a-b) and complex adaptive systems (Figure 3c-d), each described in individual sub-sections below. We subsequently discuss the implications of this conceptual approach in the section that follows.

Groundwater-connected systems as social-ecological systems

To substantiate our claim that groundwater-connected systems form social-ecological systems, we rely on the social-ecological systems framework as it is the predominant framework used in the study of social-ecological systems (Partelow 2018). In the sustainability literature, a framework is the "most general form of conceptualization; provid[ing] checklists or building blocks for consideration in constructing theories or models" (Clark and Harley 2020). The social-ecological systems framework (McGinnis and Ostrom 2014) is particularly versatile to study complex coupled human-environmental sustainability issues as it is structured to enable consideration of social and ecological components in equal depth, is multi-scalar, enables consideration of interactions and feedbacks between social and ecological processes, and provides a thorough index of social-ecological system components to possibly consider in an individual system's study (Binder et al. 2013). In the social-ecological system framework, the highest level system elements are resource systems, resource units, governance systems, and actors; and the interactions between these elements occur in the context of related ecosystems, and social, economic, and political settings (Ostrom 2007; McGinnis and Ostrom 2014). Interactions and feedbacks between social and biophysical systems occur across a multitude of time and space scales. These interactions constitute the core consideration of social-ecological system analysis (Reyers and Selomane 2018), and are represented in the social-ecological systems framework as action situations. The social-ecological system concepts is versatile and has been used across forestry (e.g. Fischer 2018), fishery (e.g. Arlinghaus et al. 2017), and water resource studies (e.g. Gain et al. 2021), in the form of qualitative and quantitative analysis, meta-analysis, comparative analysis of multiple complex adaptive system studies, as a deliberation tool, and as an underlying mental model (Partelow 2018).

In Figure 3a and 3b, we place features and processes of groundwater-connected systems within the general social-ecological system framework. This conceptualization of a groundwater-connected environment with physical, ecological, and social processes with local to global dimensions presents an improved systems-oriented foundation to understand and address complex groundwater sustainability challenges. We attribute groundwater-connected system features and elements across the social-ecological system framework categories to substantiate the inherent social-ecological system nature of groundwater-connected systems. In work framing other resource systems as social-ecological systems, the social-ecological nature of these systems is implicitly revealed through evidence of feedbacks, time lags, non-linearities, system diversity, and cross-scale dynamics (e.g. Fischer 2018; Reyers and Selomane 2018). However, we understand these attributes to be more indicative of the nature of social-ecological systems as complex adaptive systems and thus we discuss these attributes of groundwater-connected systems in the following sub-section: *Groundwater-connected systems as complex adaptive systems*. The social-ecological system framework element attributions we associate with groundwater-connected systems are meant to be simply illustrative of this conceptual alignment and are not comprehensive or immutable.

The outcomes we identify in our groundwater-connected systems conceptual model concern water, food, and energy security, biosphere integrity and planetary health, and Earth system stability. For instance, two of the example outcomes we list include *'wells running dry and reduced water security'* and *'transgressed environmental flow needs'*. We use these examples to overview how the social-ecological systems perspective facilitates a more holistic understanding of how such outcomes materialize.

In the case of *'wells running dry and reduced water security'* (which has been documented across the United States and its potential at the global scale: Perrone and Jasechko 2019; Jasechko and Perrone 2021), potential causal mechanisms of falling water tables (i.e. reductions in groundwater storage, represented as a *resource unit* in Figure 2b) include the conventional drivers of groundwater behaviour: geology, topography and climate (the *resource systems*), as well as human activity (e.g. agricultural irrigation, the dominant driver of groundwater use and consumption globally; Siebert et al. 2010) which is represented under the *actor* category. Yet, these are not the only processes and conditions that can contribute to falling water tables. Absent or ineffective regulations on groundwater use and a lack of policy coordination between food, water, and energy goals are common in areas experiencing groundwater depletion (e.g. Molle and Closas 2020; Villholth and Conti 2018; Jakeman et al. 2016). External *economic and political settings* complicate and hinder the ease of implementing policy transformations for sustainability, such as the role of global food trade networks driving unsustainable groundwater irrigation practices (Dalin et al. 2017) or the history of agricultural energy subsidization (Scott and Shah 2004). Insufficient groundwater monitoring programs, data sharing, infrastructure, and funding (aspects and products of *governance systems*) undermine anticipatory capacity of both well owners and governments, and the ability to adapt to trends in water tables will differ based on the wealth of well-owners that, for instance, dictates who can afford to drill deeper wells that keep pace with falling water tables. When groundwater depletion occurs in proximity to connected surface water bodies or terrestrial groundwater-dependent ecosystems, these interactions can also lead to transgressed environmental flow needs and degraded groundwater-dependent ecosystems. The ability to consider intersections and interactions between outcomes in groundwater-connected system processes is an advantage of adopting the social-ecological system paradigm, which can continue be applied to consider cascading impacts (e.g. see Rocha et al. 2018; Xu et al. 2021) such as impacted ecosystem services or cultural impacts of altered hydrological processes (e.g. Anderson et al. 2019).

Our inclusion of nature-based solutions (e.g. managed aquifer recharge) represents one of many possible examples of human interventions that can trigger positive change and promote sustainability in groundwater-connected systems. Thus, a social-ecological system conceptualization of groundwater-connected systems can act as a tool for more comprehensive, systems-based, solution-oriented, and place-based (locally attuned) approaches to groundwater sustainability. This perspective supports a thematic shift in the groundwater sustainability dialogue, turning away from affirmations of the ‘groundwater crisis’ and towards leveraging groundwater sustainability ‘bright spots’ (cf. Bennett et al. 2016) of promising system transformations.

Groundwater-connected systems as complex adaptive systems

While contemporary social-ecological studies have grown increasingly untethered from their complex adaptive system foundation (Preiser et al. 2018), we seek to align our framing of groundwater-connected systems with the foundational concept of *complex adaptive social-ecological system* (Levin et al. 2013). Having highlighted the social-ecological systems nature of groundwater-connected systems, we repeat this process and map the complex adaptive systems nature of the same conceptual diagram of a groundwater-connected systems environment in Figure 3c and 3d. Similar to social-ecological systems, the complex adaptive systems literature benefits from a diverse research base with no unifying, foundational theory. To confront this ambiguity and clarify which attributes are necessary for a complex adaptive system, Preiser et al. (2018) synthesized six underlying, common principles of complex adaptive systems. In the subsequent paragraphs, we summarize these common principles and discuss their representation within groundwater-connected systems to support interpretation of Figure 3c-d.

Complex adaptive systems are **constituted relationally** around network and hierarchical structures of system components, which can be diverse and heterogeneous. In a groundwater-connected environment, these relational networks can take the form of a spatially distributed set of wells across a physiographically heterogeneous and multijurisdictional landscape, international trade agreements, and multiple levels of decision making (e.g. from the United Nations Sustainable Development Goals, to national level groundwater monitoring networks (IGRAC 2020), to individual well owners' operational decisions on pumping).

Complex adaptive systems are defined, inherently, by **adaptive capacities**. The adaptive capacity of a system is a product of self-organization capabilities, decentralized control mechanisms, and the properties of system memory and resilience. In groundwater-connected systems, forms of adaptive capacity (which represent the ability of a system to respond to disturbances; Adger et al. 2011; Varis et al. 2019) include the forming of farm cooperatives and water boards, implementation of adaptive management practices, hydrogeological record keeping to inform decision making, and the implementation of nature based solutions to promote system resilience. It is also necessary to note that groundwater itself acts increasingly as an adaptive capacity through its role in underpinning water and food security as surface water availability becomes less reliable under climate change (Taylor et al. 2013).

Dynamic processes govern the behaviour of complex adaptive systems, which are characterized by multiple possible trajectories and multiple stable states (or punctuated equilibria), non-linear processes, thresholds, regime shifts, and feedback mechanisms. For example, physical system dynamic processes include groundwater-surface water interactions, which can vary across meter to watershed lengths and sub-hourly to seasonal time spans and behave non-linearly when groundwater and surface water systems become hydrologically disconnected (Brunner et al. 2011, 2017), and rainfall recharge thresholds (Baker et al. 2020). Myriad dynamic processes are visible when taking a social-ecological view of groundwater-connected systems, and include water insecurity thresholds of wells running (as aforementioned), coastal pumping inducing saline seawater intrusion (Ferguson and Gleeson 2012), groundwater depletion leading to land subsidence (Konikow and Kendy 2005), or groundwater pumping leading to streamflow depletion and transgressed environmental flow needs (Gleeson and Richter 2018; de Graaf et al. 2019). Each of these processes is the product of feedback mechanisms where social and ecological behaviour respond to the changing hydrological state (e.g. Castilla-Rho et al. 2017; Poff and Zimmerman 2010).

Complex adaptive systems are also **radically open systems**, where system boundaries are porous, with free exchange of matter, information, and energy which contribute to teleconnections and telecoupling (Liu et al. 2013). We can observe this openness in groundwater-connected systems in global virtual water trade networks, precipitationsheds (Keys et al. 2012), the expansion of groundwater resources when considering “deep” groundwater (Ferguson et al. 2021), and through open scientific practices (i.e. open-access publishing, data and code). The openness of groundwater-connected systems is also accentuated by the global impact of a small number groundwater depletion “hotspots”. This attribute of “spillover impacts [being] more significant than direct impacts” (Meyfroidt et al. 2022) is found across other social-ecological systems, and is evident in groundwater-connected systems given the state of the global groundwater crisis (Famiglietti 2014) despite the majority of groundwater systems globally being in non-stressed conditions (Gleeson et al. 2012).

Behaviour of complex adaptive systems is **contextually determined**, meaning the function of the system changes as the system changes itself, where components of the system possess multiple context-dependent identities, and where behaviour can also exhibit path dependence (i.e. is a function of both past and present system states). In groundwater-connected systems, this context dependence can take the form of groundwater storage potential before and after land subsidence (Konikow and Kendy 2005), variable human preferences and belief systems in relation to groundwater resources (Glodzik 2017), ecological sensitivity to groundwater pumping (Bierkens et al. 2021), recharge processes before and after land use change (Scanlon et al. 2005), and the impact of climate change on groundwater recharge rates (Döll 2009). The principle of contextual determination of complex adaptive systems underscores the design principle of “no panaceas” in social-ecological systems and sustainability scholarship (Ostrom 2007; Loring 2020), which directs intervention mechanisms towards locally-attuned (or place-based) approaches.

As the final common attribute of complex adaptive systems, Preiser et al. (2018) identify **emergence through complex causality**. This attribute is characterized by recursive causal mechanisms, multiple pathways of causality, the possibility for various outcomes from the same starting conditions (i.e. non-deterministic behaviour), and emergent properties. Thus, complex adaptive system behaviour is characterized by so-called INUS causes, which are "Insufficient but Necessary part[s] of a causal condition that is itself Unnecessary but Sufficient" for a specific outcome (Freese and Kevern 2013). For example, for the outcome of reduced aquatic species abundance (e.g. Poff and Zimmerman 2010), groundwater pumping is an insufficient but necessary component of a combination of causes (e.g. the aquifer being pumped also must be hydraulically connected to the stream experiencing reduced species abundance, and the resident aquatic species must be sensitive to changes in the flow regime), that together are not necessary (as other causes exist, such as land use change that impacts flow regimes) but are sufficient to decrease aquatic species abundance. This complex causality, alongside non-deterministic and emergent behaviour, complicates systems analysis as it requires greater diligence around associating mechanisms with causality and demands frequent revisiting (at different points in time and at different system states) of assumptions on causality within systems. In groundwater-connected systems, this emergence through complex causality can take the form of multiple drivers of trends of groundwater storage (e.g. Wu et al. 2020), evolution of social values of water (e.g. Wei et al. 2017), and social tipping points regarding regulations in groundwater pumping (Castilla-Rho et al. 2017).

We note that elements of common social-ecological system categories in Figure 3a-b can be found across multiple complex adaptive system principles in Figure 3c-d. While the mapping of groundwater-connected system elements to social-ecological system framework variables reveals the diverse make-up of groundwater-connected systems, this correspondence between groundwater-connected system elements to principal attributes of complex adaptive systems underscores the necessity to address the groundwater sustainability problem space from a complexity perspective.

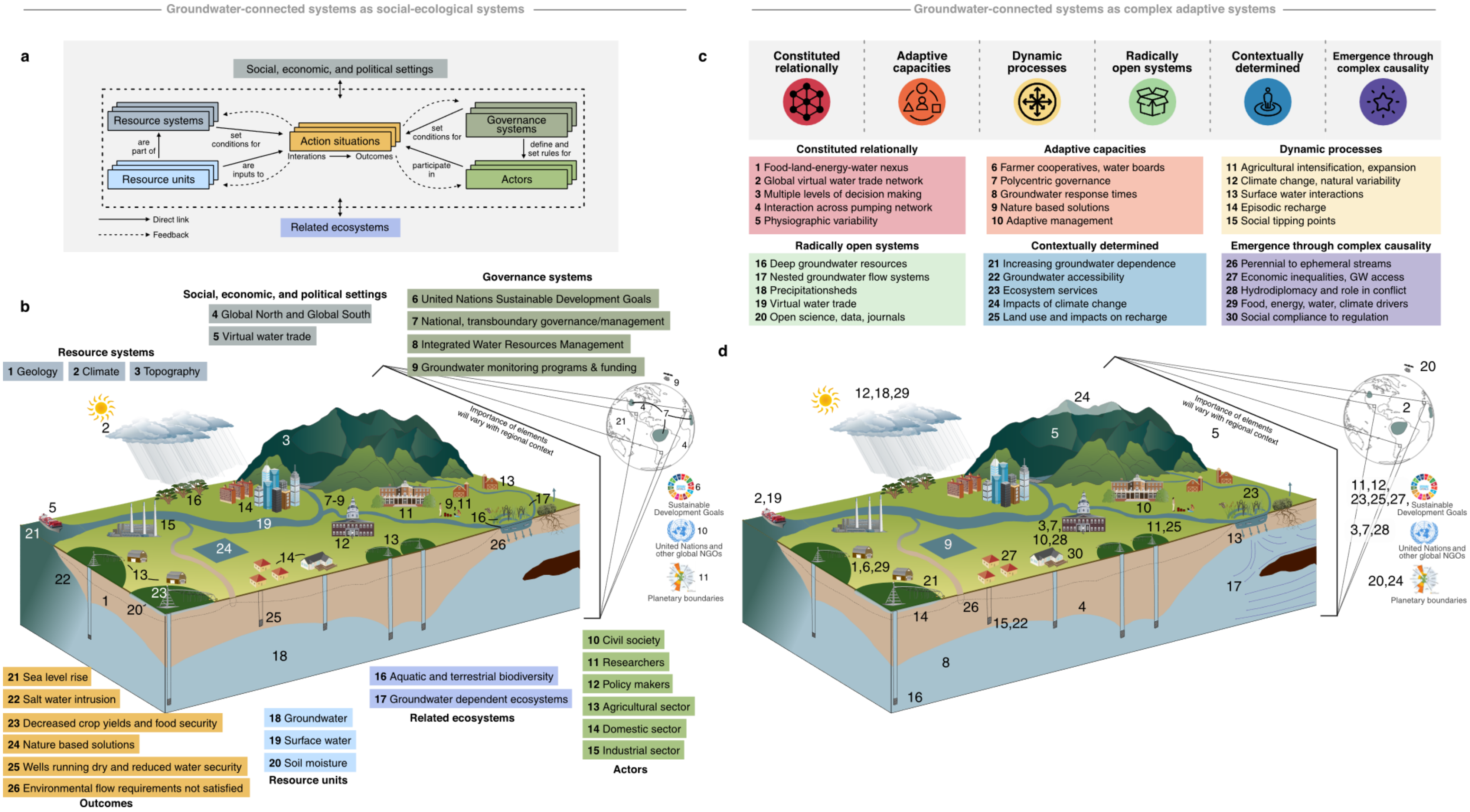


Figure 3 Groundwater-connected systems as social-ecological systems (in b), illustrated using the social-ecological systems framework (in a) redrawn from McGinnis and Ostrom (2014). Groundwater-connected systems as complex adaptive systems (in d), illustrated using the six common principles of complex adaptive systems from Preiser et al. (2018) (in c).

Implications of advancing the groundwater-connected system approach to groundwater sustainability

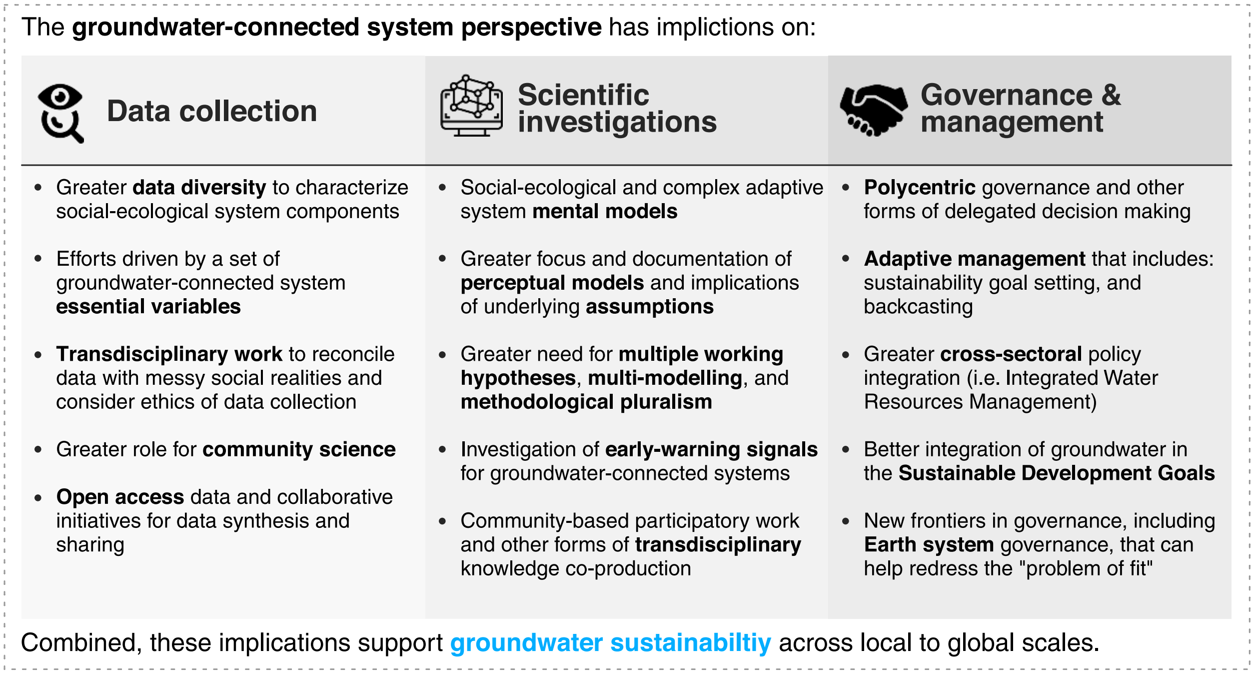
While our conceptual broadening of the groundwater sustainability problem space represents an under-voiced perspective in the literature, it simultaneously provides a foundation for a number of ongoing trends in groundwater hydrology and related fields. These include increasing interdisciplinarity (Barthel and Seidl 2017), a focus on social complexity and transdisciplinary collaborations (Re 2021), participatory modeling (Castilla-Rho et al. 2020), advocacy models (Ferré 2017) and the connected concept of multiple working hypotheses (e.g. Srinivasan et al. 2015), resilience frameworks (Hera-Portillo et al. 2021; Varis et al. 2019), social-ecological data science (e.g. Rocha et al. 2020), transdisciplinary governance initiatives (Zwarteveen et al. 2021), uncovering ecological functions of groundwater, including groundwater-dependent ecosystems (Kløve et al. 2011), environmental flow contributions (Gleeson and Richter 2018), interaction with phreatophytic vegetation (Fan et al. 2017), and the ways ecological processes impact groundwater (e.g. Hose and Stumpp 2019; Lundgren et al. 2021). Together, these developments overview the growth of socio-hydrology, socio-hydrogeology, and eco-hydrogeology, which can find a unifying conceptual foundation through groundwater-connected systems as complex adaptive social-ecological systems.

One overarching implication of the groundwater-connected system perspective that spans all discussion below is the way the perspective forces the scientist (such as the practicing hydrogeologist, the academic, etc.) to reflect on and clarify their role in supporting sustainability transformations. Given that definitions around sustainability in social-ecological systems are mired in, and inextricable from subjective, normative judgements around ‘what *should* be’ (Lélé and Norgaard 1996), the perception of ‘doing good science while holding no opinions’ is challenged. It matters not whether normative or subjective methodological decisions are made explicit (e.g. through a statement or study designed to promote a certain scenario or conceptualization) or implicit (e.g. through decisions made concerning what is studied and omitted from consideration), the scientist is an actor within this social-ecological system. This calls on researchers to place added attention on contextualizing their work as a product of their positionality, technical expertise, and specific focus, and to shy away from claims of objectivity in study outcomes.

The core tenet of social-ecological system research is to explicitly link human and natural systems, and to study these systems together as one interconnected system. This view forefronts consideration of process scale and cross-scale interactions, levels of governance, and overall system resilience (Berkes et al. 2014). Schoon and Van der Leeuw (2015) describe general implications of taking a social-ecological systems approach to study human-environmental system interactions. Comparatively, the core premise of complex adaptive systems is that certain system processes and behaviors are only visible through a systems-level perspective, and that relationships, not entities, constitute the elementary unit of analysis in complex adaptive systems (Preiser et al. 2018). These generic implications include the consideration of social and biophysical systems as a coupled, interconnected system, a need for inter- and transdisciplinary research methods, and a shift away from equilibrium-based assumptions and towards a growing focus on emergent, dynamic system processes and behavior. All of these themes are interwoven through our below discussion on implications of this perspective on data collection, science, governance, and management.

By centering relationships between groundwater and social, ecological, and Earth systems, the groundwater-connected system perspective implicitly prioritizes the resilience of these relationships such that the core functions of groundwater are retained. Simply, it is this focus on relationships and their complex behavior that is the basis for our discussion on data, science, governance, and management implications.

As most (but not all) scientific investigations and models are based on underlying data, we begin this discussion by focussing on the data collection implications of our argued perspective. However, we note the interdependency and iterative relationship between conceptual models of systems (i.e. a fundamental aspect of the scientific process) and decisions on what data to collect (and the scientific feasibility of collecting this data) render the two processes inseparable to a certain degree (cf. Clark et al. 2016).



The **groundwater-connected system perspective** has implictions on:

Data collection	**Scientific investigations**	**Governance & management**
Greater **data diversity** to characterize social-ecological system components	Social-ecological and complex adaptive system **mental models**	**Polycentric** governance and other forms of delegated decision making
Efforts driven by a set of groundwater-connected system **essential variables**	Greater focus and documentation of **perceptual models** and implications of underlying **assumptions**	**Adaptive management** that includes: sustainability goal setting, and backcasting
Transdisciplinary work to reconcile data with messy social realities and consider ethics of data collection	Greater need for **multiple working hypotheses**, **multi-modelling**, and **methodological pluralism**	Greater **cross-sectoral** policy integration (i.e. Integrated Water Resources Management)
Greater role for **community science**	Investigation of **early-warning signals** for groundwater-connected systems	Better integration of groundwater in the **Sustainable Development Goals**
Open access data and collaborative initiatives for data synthesis and sharing	Community-based participatory work and other forms of **transdisciplinary** knowledge co-production	New frontiers in governance, including **Earth system** governance, that can help redress the "problem of fit"

Combined, these implications support **groundwater sustainabiltiy** across local to global scales.

Figure 4 Implications of the groundwater-connected systems perspective on data collection, scientific investigations, governance, and management approaches.

Implications on data collection

Under the groundwater-connected systems perspective demands on data increase in a number of ways. First, there inherently becomes a requirement for more diverse data to be collected to characterize and monitor larger, more diverse, and complex systems. For example, the pertinent data space no longer pertains solely to hydrogeological processes (such as aquifer properties and water table observations) and expands to include measures of groundwater-dependent ecosystems, aquatic ecological responses to changes in groundwater discharge, well depths (not only to inform withdrawal assessments but also to understand the social risks of wells running dry), governance and socio-economic dimensions (e.g. social norms, drivers of groundwater user behaviors, sex disaggregated data, and the effectiveness of rules). The data-information-knowledge-wisdom pyramid (Rowley 2007) illustrates the foundational role data plays in generating understanding, yet little of the multi-dimensional data space that characterizes groundwater-connected systems is collected. This desired multi-dimensional data space is already being populated in related fields (e.g. see the review on socio-hydrology datasets by Lindersson et al. 2020), however groundwater research lags behind this standard.

One way to advance and consolidate more diverse data collection efforts can be to adopt the concept of “essential variables” as pursued in climate, biodiversity, ocean, and, more recently, ecosystem services literatures (Balvanera et al. 2022). Developing a standardized set of essential groundwater-connected system variables could be used to guide monitoring programs at the scale of specific aquifers or jurisdictions which would simultaneously allow for data aggregation and synthesis efforts between regions and at larger scales. For example, the extent of groundwater-dependent ecosystems, water table depths in relation to well depths and rooting depths, spatial inequalities of water accessibility within jurisdictions, virtual water flows, relationships between groundwater and surface water hydrographs, biodiversity indicators to represent aquatic ecosystem health, and surveys of social values in relation to groundwater could each constitute as essential variables to track groundwater-connected systems.

Scale is a fundamental consideration of social-ecological system analysis (Figure 2), as empirical study outcomes are conditional to their defined temporal and spatial scales and local-scale studies cannot be simply aggregated to explain large-scale phenomena as larger-scale processes (i.e. large scale processes are often a non-linear consequence of smaller-scale processes). More comprehensive and synchronized data collection efforts would prove valuable to understanding complex cross-scale interactions. Yet, collecting such data presents practical challenges regarding the capacity to analyze and extract knowledge from such information.

Expanding data collection is particularly challenging for governance systems, which can include pluralities of networked public, private and non-government actors, norms, regimes, decision making and operational rules (McGinnis and Ostrom 2014; Villholth et al. 2018). These and other governance variables are often constituted by scale, geography and history, yet are continually evolving and contested (McGinnis and Ostrom 2014; Short 2021; Allison et al. 2021). Indicators and data on such "messy" social and political realities are improving, yet determining who governs and how they govern remain issues that require careful exploration through empirical and context specific research (see e.g. Holley and Shearing 2017; Mair et al. 2018). While governance scholars have begun to identify methodological and conceptual approaches to guide these efforts (Shearing and Johnston 2003; Curtis et al. 2016; McGinnis and Ostrom 2014), they continue to be debated and are rarely determined easily (Holley and Shearing 2017). For instance, the nation-scale worldwide governance indicators initiative has been scrutinized for its ability to faithfully represent core, independent dimensions of governance (see Langbein and Knack 2010; Thomas 2010). While these criticisms are currently not part of the groundwater sustainability dialogue, they are necessary when considering the social-ecological resilience of a groundwater-connected system (cf. Varis et al. 2019).

One opportunity to address data deficiencies is to embrace the potential of community or citizen science (Buytaert et al. 2014), particularly where groundwater-connected systems are undergoing rapid change. There is widespread evidence of the role community science can play in not only filling observation deficiencies but in increasing social awareness around change in human-environmental systems (Kimura and Kinchy 2016). Community science and the related approach of community-based participatory research are discussed more in the sub-section *Implications on scientific investigations.*

This call for greater, more diverse data collection requires careful consideration to what data is not only practical but ethical to obtain. Zipper et al. (2019) provide guidance in navigating the open science-data privacy dilemma in socio-hydrology. In transdisciplinary collaborations, particularly those that work across knowledge systems (e.g. between western science and Indigenous knowledge systems) greater care and diligence is needed when collecting and handling data.

Yet, data-driven evidence underscores the ability to make generalized knowledge claims (Magliocca et al. 2018) and to adequately establish necessary and/or sufficient conditions in complex causal mechanisms. Thus, there is not only a need to accelerate more comprehensive data collection efforts that span the groundwater-connected system problem space but to also synthesize such efforts via open access initiatives. Such efforts are already being pursued across other social-ecological system problem domains, such as the Nature Map Earth (https://naturemap.earth/), which can offer a template for the groundwater sustainability research community to follow. Such databases could be very powerful to use in conjunction with the existing social-ecological system regime shift databases that exist (e.g. the Regime Shifts Database (Biggs et al. 2018), the Social-Ecological Systems Meta-Analysis Database, (SESMAD

2014), and the Thresholds Database (Resilience Alliance and Santa Fe Institute 2004). One example integration of these data resources could be to compare social-ecological system data to groundwater-related regime shifts in the aforementioned databases to identify conditions that promote or hinder regime shifts within groundwater-connected systems.

Implications on scientific investigations

An implicit but profound implication the groundwater-connected system perspective imparts on scientific investigations is the re-constituting of traditional mental models underpinning research. This rethinking of theoretical foundations is a core implication of the social-ecological system perspective, which has permeated other social-ecological domains (Schoon and Van der Leeuw 2015), but has yet to be adopted in groundwater research. Conceptualizing the groundwater sustainability problem space through the lens of groundwater-connected systems reframes issues, fundamentally, as interdisciplinary, complex system challenges (as outlined in Figure 1).

There is a wide and rich literature on complex adaptive social-ecological system approaches to confronting human-environmental sustainability challenges (Biggs et al. 2021). The most natural entry point into this field is through common frameworks and models of this literature. For example, a foundational model to resilience thinking in complex social-ecological systems is the ball and basin model (Walker and Salt 2006). The ball and basin model depicts the state of the system based on the location of the ball and the “topography” as all possible sets of system variables (i.e. the state space), with the number of “basins” representing alternative stable system states. The ball and basin model thus visualizes alternative system stable states (i.e. individual ‘basins’), thresholds, and system resilience to perturbations (i.e. through the ‘depth of basins’). Myriad other frameworks and models exist to study social-ecological systems, such as the panarchy framework to study ‘slow’ and ‘fast’ change in social-ecological systems, ecosystem services and cultural ecosystem services frameworks (e.g. Millenium Ecosystem Assessment 2005; Chan et al. 2012), various vulnerability frameworks (e.g. Turner et al. 2003), and many more. For a review of common frameworks to study social-ecological systems, see Binder et al. (2013).

These models and frameworks can subsequently influence the development of conceptual models that underpin groundwater sustainability studies, including process-based models (Clark et al. 2016). The inherent diversity of approaches to groundwater-connected system challenges requires greater focus be placed on documenting these new conceptual models. Doing so not only aids identification of the merits and focus of a given model, but explicitly highlights the processes considered and omitted from representation, their limitations, and the uncertainties they introduce (Wagener et al. 2021). Such documentation places greater emphasis on identifying, clarifying, justifying, and confronting core assumptions of analysis. In complex adaptive social-ecological systems, studies focussing exclusively on physical, ecological, or social system components (or combinations thereof) will require greater clarification of boundary conditions, system definitions, and the implications of these methodological decisions. This added rigor to documenting underlying model assumptions is not to be viewed as a purely academic exercise, and rather aids in placing each work in a broader, holistic groundwater-connected system context.

This focus on uncovering assumptions is consistent with recent calls in the groundwater modeling literature (i.e. “assumption hunting” in Peeters 2017) but now extends across a wider, interdisciplinary domain. While proposing a systematic protocol to document models of groundwater-connected systems is beyond the scope of this work, a prominent example to consider as a baseline could be the ODD protocol used for documenting agent-based models

(Grimm et al. 2020). Such a protocol, should it be developed, would be useful in guiding the documentation of groundwater-connected system studies.

Greater documentation of conceptual models in groundwater sustainability research will facilitate comparison between models and the easier identification of methodological and conceptual gaps in existing studies. Such comparisons need not be viewed in a confrontational light (i.e. pitting model vs. model), but rather can be used as a tool to develop multiple working hypotheses on the behavior of complex systems.

To address prediction uncertainty given stark structural differences between hydrological models, the method of multiple working hypotheses via an ensemble-of-models approach has already been advocated for and applied in the hydrological modeling community (Clark et al. 2011). Moving towards ‘multi-modeling’ has also been argued for in groundwater modeling (Ferré 2017; MacMillan 2017). The groundwater-connected systems perspective likewise supports the implementation of multiple working hypotheses where an ensemble of alternative plausible models, each of which individually cannot provide a single true answer (Castilla-Rho et al. 2020), can be compared for a given groundwater issue in order to derive actionable conclusions.

As argued by Page (2018), this many-model paradigm can lead to wiser choices, more accurate predictions, better constrained uncertainty, and more robust designs. Ensemble-of-models approaches should be pursued for topics concerning complex groundwater-connected systems, which are characterized by less process understanding and greater uncertainty relative to groundwater hydrology. Multi-modelling does not need to take any particular form, and can be used to integrate methodologically pluralistic studies to identify common outcomes and areas of convergence and divergence. Furthermore, multi-modeling as a practice better reflects the multiple partial perspectives that characterize sustainability discourses, where a sustainability-related challenge does not possess a single optimal solution but rather a multiplicity of partial solutions that require reconciling. Examples of this methodological pluralism in the groundwater-connected system modeling space include system dynamics, agent-based simulation, or a traditional groundwater model—each with its own strengths and blind spots. We overview these among other method alternatives, briefly, below.

Agent-based models are generative social models that are coupled to an environment (Epstein and Axtell 1996) and are a perfect opportunity for exploratory and scenario-based modeling in groundwater-connected systems (Zellner 2008; Castilla-Rho et al. 2015). Agent-based models diverge from equilibrium-based systems analysis by simulating agent behavior through a set of agent-agent and agent-environment interactions that can better represent the bounded rationality of agent behavior and produce emergent, complex behavior outcomes. Agent-based models represent a practical and pragmatic way to build artificial laboratories to safely experiment on and design human-groundwater systems, though challenges remain in representing more-complex hydrogeological processes and have yet to be coupled with any form of ecological consideration. The overarching challenge of groundwater agent-based models, and to groundwater-connected system modeling in general is "finding the complexity that matters" (Castilla-Rho 2017). Interdisciplinary work between groundwater hydrologists and social scientists, and transdisciplinary collaborations with stakeholders can aid in locating this balance.

Other analytical approaches that are available to advance understanding of groundwater-connected systems include systems dynamics modeling (Mashaly and Fernald 2020) and interdisciplinary data science models. Systems dynamics models help develop understanding of relationships between diverse systems components and the behavior and outcomes their interactions produce, and can aid in pin-pointing locations within systems where specific process knowledge is lacking to target for further investigation.

Data driven analysis of complex adaptive systems has produced generic principles to identify early-warning signals for threshold transgressions (Scheffer et al. 2009). These early warning signals include critical system “slowing down” and “flickering”, and prelude a system moving from one stable state into another. Though these generic principles have been applied to other complex human-environmental systems (e.g. Bauch et al. 2016), such investigations have yet to be applied to groundwater-connected systems.

Alternatively, interdisciplinary data science is a methodological approach that has emerged over the last decade across the social-ecological system literature to operationalize social-ecological system concepts through spatially-explicit indicator development (e.g. Leslie et al. 2015; Williamson et al. 2018; Rocha et al. 2020). Such studies are useful in identifying macro-level conditions that characterize a social-ecological system which can dictate how or what intervention mechanisms are pursued, can act as an aggregate indicator of the state of a social-ecological system with respect to certain sustainability-related policy goals, and can help identify relationships between social and ecological system states. This form of analysis can be particularly useful for groundwater sustainability transformations. For instance, taking the example of managed aquifer recharge, one could ask: what are the macro-scale social, economic, governance, political, and hydrogeological conditions that are most common in successful implementations of managed aquifer recharge projects, and what conditions typically characterize ineffective managed aquifer recharge initiatives?

Such multi-model analysis and methodological pluralism is crucial to embedding a core tenet of social-ecological system-informed sustainability science in the groundwater sustainability discourse: that there are no panaceas (Loring 2020) and that solutions must be attuned to local hydrogeological, ecological, economic, and cultural conditions.

The groundwater-connected systems perspective also creates space for greater adoption of community-based participatory research that enables knowledge co-production in transdisciplinary settings. Such knowledge co-production, that can involve participatory modeling approaches (Castilla-Rho et al. 2020), can facilitate the integration of multiple knowledge bases and can help ensure that research better reflects local stakeholder values and relationships with respect to groundwater. Simultaneously, such transdisciplinary work can strengthen scientific practice and output by canvassing a larger evidence base to inform studies (Tengö et al. 2014).

Implications on governance and management

Although a full discussion on the implications of groundwater-connected systems perspective on the linked but discrete domains of groundwater governance and management is outside of the scope of this paper, we include a brief discussion here as to not indicate there are less implications on these components of groundwater sustainability.

Shifting from resource-centric thinking to a complex adaptive social-ecological systems approach can avoid traditional tendencies of disconnecting groundwater resources from their social context. In doing so, it rejects the types of simplistic and uniform thinking that has led to failed top-down, technical and one-size-fits-all governance designs (Closas and Villholth 2020). Instead, the social ecological systems lens recognises integrated and connected governance systems as social and political phenomena (Closas and Villholth 2020). In this way, it unlocks opportunities for more tailored and orchestrated polycentric governance solutions that, under the right conditions, can support more democratic, sustainable, and resilient outcomes (McGinnis 2016).

Building on participatory modeling opportunities discussed above, and the natural orientation of the groundwater-connected system perspective against equilibrium-based system approaches, the groundwater-connected system perspective, as we articulate it, supports the linking of adaptive management and participatory modeling processes (Crevier and Parrott 2019). Such adaptive management approaches need to be underpinned by sustainability goal setting and backcasting (Gleeson et al. 2012). Sustainability goals in groundwater-connected systems can be informed by multi-objective initiatives such as the Sustainable Development Goals or by downscaling other quantitative sustainability initiatives, such as the planetary boundaries (Zipper et al. 2020).

Groundwater is notably underrepresented in the Sustainable Development Goals (Gleeson et al. 2020), yet it is connected to nearly half of Sustainable Development Goal targets (Guppy et al. 2018). Similarly, a biosphere based conceptualization of the Sustainable Development Goals locates freshwater as foundational to the initiative (Folke et al. 2016). A groundwater-connected systems perspective supports the consideration and thus inclusion of groundwater in such interdisciplinary, multi-objective initiatives and helps confront the “overlooked” and “invisible” history of groundwater.

The integrated nature of this groundwater-connected system perspective lends towards greater representation of integrated, cross-sectoral policy development, which can further substantiate the integrated water resources management (IWRM) and food-energy-water nexus management paradigms (Scanlon et al. 2017; Agarwal 2000). The multi-scale nature of the groundwater-connected system perspective can also facilitate integration of cross-scale interactions that are needed to respond to burgeoning understandings of Earth systems and their governance (Kotzé et al. 2022). One example of this is found in integrating the planetary boundary framework across global to local scales (Zipper et al. 2020). Such cross-scalar management approaches are necessary as scale mismatches often exist between human action and environmental systems in space, time, and/or function.

Often called ‘the problem of fit’ or ‘scale mismatch’, management practices occur at usually local and regional levels which do not match those of biophysical systems which are not constrained to political boundaries or human time frames (Cumming et al. 2006; Epstein et al. 2015). A multi-scalar social-ecological system perspective may prove beneficial in beginning to redress the problem of fit for groundwater-connected systems in contrast to dominant management paradigms that predominantly focus on individual scales, do not consider cross-scale interactions, and largely are absent or in initial management stages across most of the world (Villholth and Conti 2018).

Conclusion

In closing, we return the premise of Schwartz’ *Groundwater* editorial “Zombie-Science and Beyond” (2013). Our ambition for this paper is to provide one possible theoretical foundation and methodological roadmap for embracing complexity and interdisciplinarity in groundwater research. Ney and Verweij (2015) argue that ‘wicked’ problems are addressed through ‘clumsy’ solutions. The groundwater-connected systems perspective we have outlined embraces the ‘wickedness’ of the global groundwater crisis and equips groundwater sustainability scientists with the tools to explore ‘clumsy’ solutions.

Yet, the groundwater-connected system perspective we articulate does not provide explicit solutions to address the groundwater crisis, and we believe no such framing could. Rather, in our view, the paradigms, frameworks, models, and methods introduced or amplified by the perspective can act as more capable *tools* to develop locally-attuned interventions and solutions.

We see the groundwater-connected systems perspective as providing a form of “connective tissue” to enable greater interdisciplinary and transdisciplinary collaborations and put data, science, governance, and management on track to better affect sustainable groundwater futures. We envision the groundwater sustainability literature as becoming more complex yet also more nuanced, more deeply connected to underlying sustainability and complexity science foundations, and ultimately more effective. Bright spots exist for sustainable groundwater transformations (e.g. Zwarteveen et al. 2021; Gleeson 2020), and we believe embracing the groundwater-connected systems perspective will generate more.

Author contributions

X.H. conceived the issue paper with advice from T.G., J.C.R., and J.S.F.

X.H. produced all figures, with input on Figure 1 from: T.G., J.C.R., and J.S.F., Figure 2 from: J.C.R., Figure 3 from: T.G. and J.C.R., and Figure 4 from: T.G., J.C.R., V.R., and C.H.

X.H. lead writing, and all co-authors (T.G., J.C.R., C.H., V.R., and J.S.F.) edited and discussed the manuscript at multiple stages.

Acknowledgements

X.H. was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada through an Alexander Graham Bell Canada Graduate Scholarship. J.C.R and C.H. were supported by an Australian Research Council Discovery Project grant (DP190101584).

Figure 3 was produced by the authors by modifying and assembling individual vector symbols from the Integration and Application Network (ian.umces.edu/media-library) under CC BY-SA 4.0. Artists of individual symbols used are: Catherine Collier, Jason C. Fisher, Alexandra Fries, Jane Hawkey, Max Hermanson, Kim Kraeer, Emily Nastase, Tracey Saxby, Dylan Taillie, Jane Thomas, and Lucy Van Essen-Fishman.

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