This is a non-peer reviewed preprint submitted to EarthArXiv. The manuscript is in review in *Groundwater*.

Second revision:

Issue Paper/

Groundwater connections and sustainability in social-ecological systems

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Conflict of interest: None

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

Article Impact Statement: Introduces the *groundwater-connected systems* framing.

Abstract

Groundwater resources are connected with social, economic, ecological, and Earth systems. We introduce the framing of *groundwater-connected systems* to better represent the nature and complexity of these connections in data collection, scientific investigations, governance and management approaches, and groundwater education. Groundwater-connected systems are social, economic, ecological, or Earth systems that interact with groundwater, such as irrigated agriculture, groundwater-dependent ecosystems, and cultural relationships to groundwater expressions such as springs and rivers. Groundwater-connected systems form social-ecological systems with complex behaviours such as feedbacks, non-linear processes, multiple stable system states, and path dependency. These complex behaviours are only visible through this integrated system framing and are not endogenous properties of physical groundwater systems. The framing is syncretic as it aims to provide a common conceptual foundation for the growing disciplines of socio-hydrogeology, eco-hydrogeology, groundwater governance, and hydro-social groundwater analysis. The framing also facilitates greater alignment between the groundwater sustainability discourse and emerging sustainability concepts and principles. Aligning with these concepts and principles presents groundwater sustainability as more than a physical state to be reached that additionally must integrate place-based and multi-faceted goals, values, justice, knowledge systems, governance and management to maintain groundwater's social, ecological, and Earth system functions. The groundwater-connected system framing can underpin a broad, methodologically pluralistic, and community-driven new wave of data collection and analysis, research, governance, management, and education. These developments, together, can invigorate efforts to foster sustainable groundwater futures in the complex systems groundwater is embedded within.

Seeing groundwater through its connections

Groundwater is often described as a uniquely invisible, slow, and distributed resource (Villholth and Conti 2018; Gleeson et al. 2020). In this work, we seek to add a fourth quality to this description: groundwater as a connected resource. We make the case that a focus on groundwater's connections to social, economic, ecological, and Earth systems can generate novel insights, and more effective, socially relevant outcomes.

Groundwater is linked to many societal and environmental challenges and is a resource deeply embedded in a global crisis (Famiglietti 2014). Yet, it is often under-prioritised or omitted in political and social agendas (Global Groundwater Statement 2019). Simultaneously, there are calls for creativity and greater methodological experimentation in groundwater research (Schwartz 2013). To what degree might a reliance on dominant conventions be linked or even contribute to the depleted and overlooked state of groundwater today? And, in what direction should groundwater practice and research expand to better address these intersecting challenges?

Amid calls for innovation in groundwater research, substantial progress has been made to document groundwater interactions and relationships in social, ecological, and Earth systems. This progress is found in the emerging disciplines of socio-hydrogeology (Re 2015), eco-hydrogeology (Cantonati et al. 2020), groundwater in Earth systems science (Gleeson et al. 2020), and transdisciplinary methods (Zwarteveen et al. 2021); and the more established social science domains of common pool resource governance (Curtis et al. 2016; Mukherji and Shah 2005) and analysis of hydro-social systems (Wesselink et al. 2017). The intricate nature and complexity of these interactions reveal the need to study, use, and manage groundwater resources on the basis of the functions and services that groundwater provides to systems that interact with it. Taking methodological and practical steps in this direction are necessary to ensuring long-term sustainability and resilience in systems connected to groundwater.

We introduce a new framing for groundwater systems that we call *groundwater-connected systems*. The potential for this framing is two-fold. First, it can provide a common conceptual foundation for both traditional research programs and emerging, diverse research programs that document groundwater interactions with a broad and expanding set of systems. Second, it can facilitate the application of paradigms, methods, and theories from the emerging field of sustainability science to groundwater topics that, in our view, have been underutilised to date.

This new framing supports the growth of groundwater research from a predominantly disciplinary pursuit—focused on groundwater as an isolated resource and one dominated by hydrogeologists' perspectives, methods, and paradigms—to an interdisciplinary pursuit focused on documenting groundwater interactions and relationships with social, ecological, and Earth systems through transdisciplinary methods and collaborations (Figure 1a).

There is a long history in the social sciences of documenting many of these interactions and dynamics (Ostrom 1990). Yet, motivating this paper and the groundwater-connected systems framing are two notions. The first is that these foundational concepts and research questions remain largely unknown or rest in the peripheral awareness of many hydrogeologists, the dominant discipline in groundwater dialogues. A greater ability to engage in interdisciplinary discourse and science amongst hydrogeologists is needed for effective participation in applied groundwater studies and management initiatives. The second is that we perceive unfulfilled potential for social scientists to represent biophysical (e.g., hydrogeological, ecological, Earth system) dynamics with greater process specificity, and to operate at larger spatial scales of analysis, which are both needed to address a wider array of groundwater related interactions and challenges.

Our intention for the framing is to facilitate novel, methodologically pluralistic work on diverse groundwater topics to produce outputs more aligned with issues of ecological and societal concern. By making relationships between groundwater with social, economic, ecological, and Earth system processes better understood and more visible, our framing can help redress the often overlooked nature of groundwater and elevate the relevance and prioritisation of groundwater in social and policy discourses.

We begin by introducing our framing of '*Groundwater-connected systems*'. We then discuss the wider potential for sustainability science methods and concepts to be applied to groundwater sustainability topics in '*Invigorating groundwater sustainability with sustainability science*'. We end by providing a set of possible implications the framing can impart on data collection, scientific investigations, governance and management, and education in '*Wide applicability to groundwater science and beyond*'. Key terms are defined in Table 1.

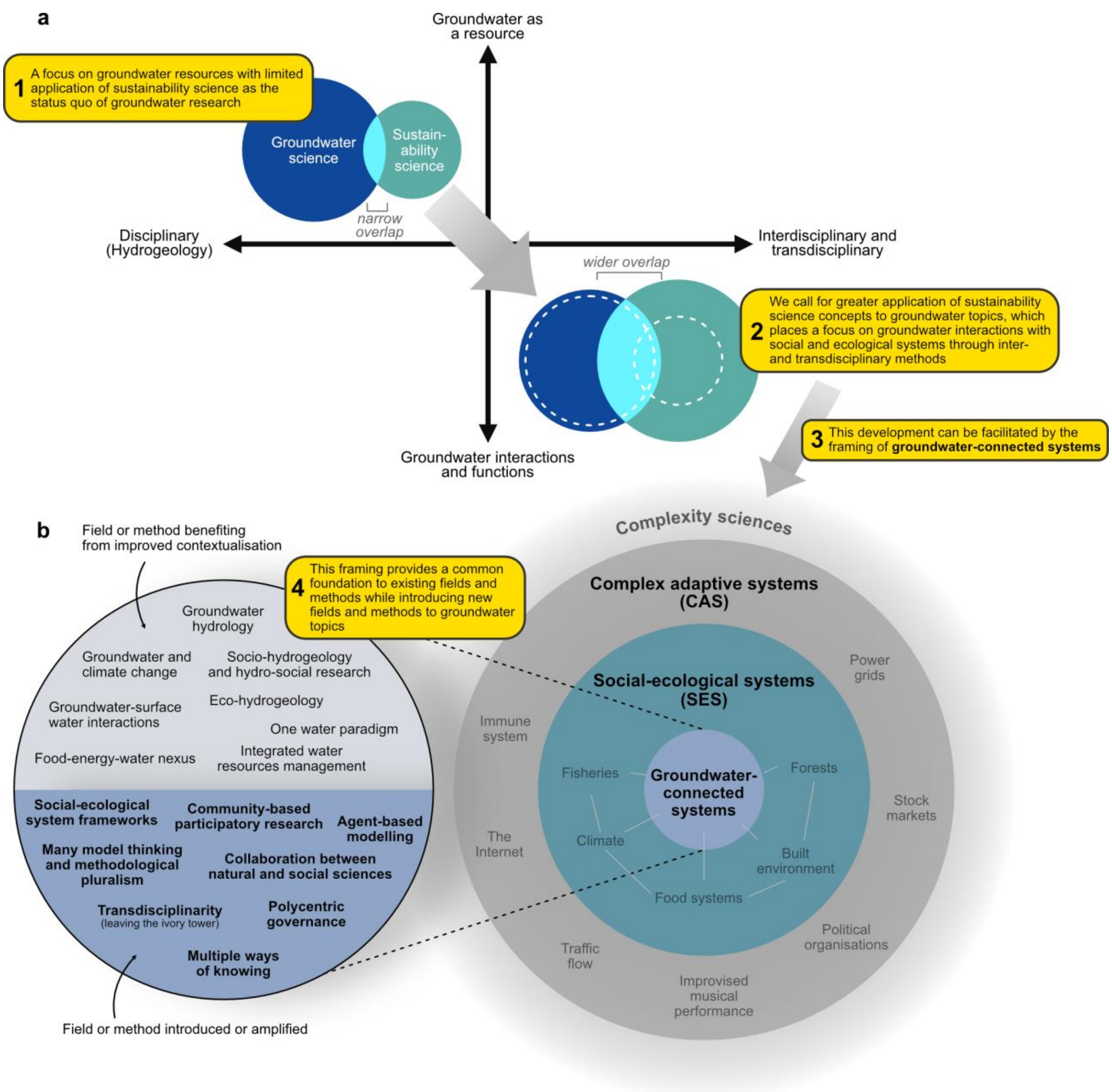

Figure 1. Groundwater groundwater-connected systems as a framing for groundwater practice and research. (a) We argue that groundwater investigations and assessments should increasingly move from disciplinary pursuits focusing on physical groundwater systems to inter- and transdisciplinary collaborations that focus on understanding groundwater interactions and functions in larger connected systems. (b) This new framing is enabled by understanding groundwater-connected systems as social-ecological systems, which introduces new methods or amplifies existing methods for data collection, research, governance and management approaches, and education. To support interpretation of this figure, consult the yellow text boxes in their numbered order.

Table 1: Summary of terminology used in this paper.

Term	**Definition**	**Core properties**	**Key references** **(● review article)**
Groundwater-connected system	A system that is formed between physical groundwater systems and any social, ecological, or Earth system(s).	Shared with social-ecological systems and complex adaptive systems.	This work
Social-ecological system	An integrated system formed by interactions between social and biophysical systems.	Social-ecological systems are forms of complex adaptive systems, with: Thresholds, Multi-scalar dynamics, Feedbacks, Non-linear processes, Multiple stable states, Time lags, and Path dependency	Ostrom (1990) Berkes and Folke (1998) Ostrom (2009) ● de Vos et al. (2019)
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).	Dynamic processes, Relational networks, Open systems, Context-dependent behaviour, and Emergent behaviour	Levin et al. (2013) ● Preiser et al. (2018)

Sustainability science	A science that focuses on the “interactions between natural and social systems, and with how those interactions affect the challenge of sustainability” (Kates 2011).	Undisciplinary, Problem oriented, Complexity, Collaborative institutions, Multiple ways of knowing, No panaceas, and Adaptation	Kates (2011) Jerneck et al. (2011) Loring (2020) ● Clark and Harley (2020)
Wicked problem	Problems that are not easily defined or solved due to their embeddedness in complex social contexts, having no single or straightforward solution.	Unintended consequences, No clear stopping criterion, Multiple, contradictory perspectives framing problem, and Unclear definitions of ‘good’ or ‘bad’ outcomes	Rittel and Webber (1973) Crowley and Head (2017) ● Lönngren and van Poeck (2021)

Groundwater-connected systems

Here, we introduce the framing of groundwater-connected systems. Groundwater-connected systems are formed between physical groundwater systems and any social, ecological, or other biophysical system(s) that interacts with groundwater (Table 1). Thus, groundwater-connected systems take many forms. Groundwater irrigated agriculture, domestic well owner’s water security, groundwater institutions, management initiatives, and the cultural values associated with surface expressions of groundwater, such as river baseflow and springs, are a few human-oriented examples of groundwater-connected systems. Ecological and biophysical examples include terrestrial, aquatic, and subterranean groundwater-dependent ecosystems, groundwater-atmosphere process coupling, coastal ecosystems that rely on groundwater discharge, and groundwater-aquatic biodiversity relationships such as ecological responses to transgressed environmental flow requirements. Groundwater-connected systems are also the network of interactions between these often intertwined systems.

We understand groundwater-connected systems as forms of social-ecological systems (Figure 2). Social-ecological systems offer a way of viewing human-environmental system interactions as a single, interconnected system with physical, ecological, and social components (Berkes and Folke 1998). Social-ecological systems are characterised by complex adaptive system behaviours (Levin et al. 2013; Preiser et al. 2018) such as thresholds, feedbacks, non-linear processes, multiple stable system states, path and context dependent behaviour and emergent phenomena (Table 1). While physical groundwater systems are naturally dissipative and are themselves not social-ecological systems, these physical systems (i.e., aquifers) are components of social-ecological systems through their social, ecological, and biophysical interactions.

The groundwater-connected systems framing is flexible and does not provide an explicit or finite set of system interactions to study. Rather, the framing argues that a focus on relationships and interactions between groundwater and other systems offers critical insights that are unattainable when studying the resource in isolation.

This focus on relationships rather than entities is consistent with motivations of the broader social-ecological systems literature (Reyers and Selomane 2018). The subsetting of groundwater-connected systems, social-ecological systems, and complex adaptive systems (shown by the nested circles in Figure 1b) locates groundwater-connected systems research as a complexity discipline.

In Figure 2a, we present a conceptual diagram of groundwater-connected systems as social-ecological systems. For this illustration, we use the structure of the Social-Ecological Systems Framework (McGinnis and Ostrom 2014; Figure 2b), the predominant framework used in the study of social-ecological systems (Partelow 2018). We associate features and processes of groundwater-connected systems to the generic structure of the social-ecological system framework. These attributions are not comprehensive but provide evidence to support the view of groundwater-connected systems as social-ecological systems. For an extended description of Figure 2a, see the Supporting Information.

Interactions and feedbacks in social-ecological systems occur across multiple space and time scales (Chapin et al. 2009). The relationship between international food trade, groundwater depletion, and environmental flows represents one example of cross scalar interactions in groundwater-connected systems. International food trade networks drive groundwater depletion (Dalin et al. 2017) that manifests as local to regional scale drawdown of the water table. Falling water tables can subsequently have cascading impacts on aquatic ecosystems that depend on groundwater discharge. For example, environmental flow transgressions driven by reduced groundwater discharge can lead to reach-scale impacts on fish populations, aquatic ecologies, and riparian vegetation (Gleeson and Richter 2018). Thus, social-ecological systems analysis attempts to understand how outcomes emerge through biophysical and social interactions, which often embody properties of complex adaptive systems (Figure 2c). For instance, groundwater-pumping induced land subsidence can irreversibly change aquifer storage capacity, reducing the ability of groundwater to act as a buffer in times of drought which can decrease agricultural productivity and force shifts to alternative land uses (Dinar et al. 2021). These dynamics offer examples of thresholds, feedback mechanisms, path-dependent behaviour and regime shifts common to complex adaptive systems. See Table S1 for more information on complex adaptive system properties and behaviours of groundwater-connected systems.

While many of these interactions and outcomes remain undocumented, excluded, or under-analysed, a growing body of literature across the natural and social sciences is beginning to examine the complex characteristics, processes, and outcomes of groundwater interactions in social-ecological systems. Examples of studies from the natural sciences include nonlinear influences of groundwater on ecosystem services (Qiu et al. 2019), groundwater depth thresholds to maintain tree canopy condition (Kath et al. 2014), regional precipitation patterns driven by distal groundwater irrigation (Lo and Famiglietti 2013), and alternate stable states in groundwater-stream interactions (Zipper et al. 2022). In the social sciences, from which the social-ecological systems concept emerged, example studies include general design principles for self-sustaining irrigation institutions (Ostrom 1993), identification of nested institutional arrangements in local irrigation communities (Cox 2014), farmer adaptations to reduced groundwater availability (Running et al. 2019), the perception of fairness in groundwater allocation (Hammond Wagner and Niles 2020), socio-historical studies on the social and political contexts that lead to successful implementation of managed aquifer recharge projects (Richard-Ferroudji et al. 2018), Indigenous knowledge systems in relation to water (McGregor 2012), and analysis on the ability of low income, rural stakeholders to meaningfully participate in groundwater governance processes (Dobbin 2020). There is also a third grouping of emerging interdisciplinary studies (Barthel and Seidl 2017), which include suitability analysis of managed aquifer recharge that considers both physiographic setting and institutional design (Ulibarri et al. 2021), studies on interactions between groundwater user behaviours, social norms, and physical groundwater dynamics to establish rules for more sustainable groundwater management (Hammani et al. 2009), and evaluations of the effect and timing of initiatives to promote groundwater recharge (Patel et al. 2020).

Thus, we are far from the first to recognize the potential for a social-ecological framing to be applied to groundwater topics and to the groundwater sustainability discourse. However, amid this rich and diverse set of studies, we perceive a lack of foundational literature that integrates emerging trends in groundwater research though a common conceptual foundation. Furthermore, while these outcomes are often included in discussion sections of hydrogeological studies, they remain rarely modelled or explicitly considered in analysis. These relationships and outcomes become the explicit focus of analysis for groundwater-connected systems. Thus, our framing is syncretic in that it aspires to tie together and build on emerging trends in groundwater-related disciplines. Viewing these various research trends, overviewed above, through the common foundation of groundwater-connected systems can facilitate greater awareness, dialogue, and collaboration between these research communities. Furthermore, the framing can provide a useful foundation to support the construction of hypotheses and to generate narratives about change in social-ecological systems connected to groundwater.

To illustrate the potential to facilitate more systematic, holistic problem understanding that brings together multiple knowledge bases and data formats, we use an example outcome from Figure 2a: ‘*dry wells and reduced rural water security*’ in the setting of California’s Central Valley (Box 1). We argue that taking such a holistic systems view, regardless of the type of analysis to be conducted, supports a more rigorous identification of study assumptions, limitations, and potential in-roads across disciplines than when approached exclusively from narrowly defined disciplinary perspectives. Other benefits of this framing extend across data collection, scientific investigations, governance and management, and education topics, which the remainder of this paper is allocated to the discussion of.

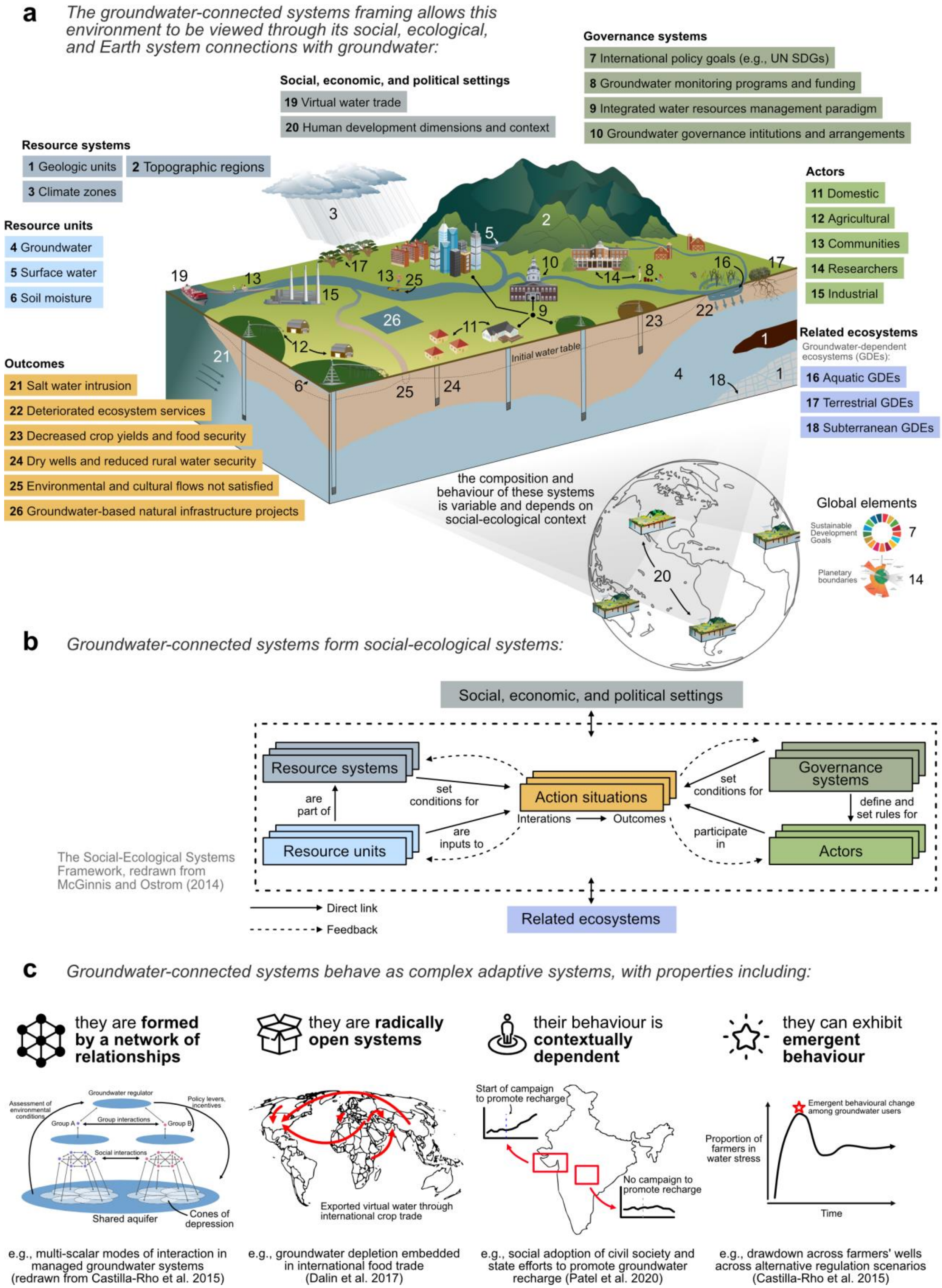
a
The groundwater-connected systems framing allows this environment to be viewed through its social, ecological, and Earth system connections with groundwater:
Social, economic, and political settings
19 Virtual water trade
20 Human development dimensions and context
Governance systems
7 International policy goals (e.g., UN SDGs)
8 Groundwater monitoring programs and funding
9 Integrated water resources management paradigm
10 Groundwater governance intitutions and arrangements
Resource systems
1 Geologic units
2 Topographic regions
3 Climate zones
Resource units
4 Groundwater
5 Surface water
6 Soil moisture
Actors
11 Domestic
12 Agricultural
13 Communities
14 Researchers
15 Industrial
Related ecosystems
Groundwater-dependent ecosystems (GDEs):
16 Aquatic GDEs
17 Terrestrial GDEs
18 Subterranean GDEs
Outcomes
21 Salt water intrusion
22 Deteriorated ecosystem services
23 Decreased crop yields and food security
24 Dry wells and reduced rural water security
25 Environmental and cultural flows not satisfied
26 Groundwater-based natural infrastructure projects
Initial water table
the composition and behaviour of these systems is variable and depends on social-ecological context
Global elements
Sustainable Development Goals
Planetary boundaries
b
Groundwater-connected systems form social-ecological systems:
Social, economic, and political settings
Resource systems
Action situations
Governance systems
are part of
set conditions for
set conditions for
define and set rules for
Interations
Outcomes
Resource units
are inputs to
participate in
Actors
The Social-Ecological Systems Framework, redrawn from McGinnis and Ostrom (2014)
Direct link
Feedback
Related ecosystems
c
Groundwater-connected systems behave as complex adaptive systems, with properties including:
they are formed by a network of relationships
they are radically open systems
their behaviour is contextually dependent
they can exhibit emergent behaviour
Groundwater regulator
Assessment of environmental conditions
Policy levers, incentives
Group A
Group interactions
Group B
Social interactions
Shared aquifer
Cones of depression
Exported virtual water through international crop trade
Start of campaign to promote recharge
No campaign to promote recharge
Emergent behavioural change among groundwater users
Proportion of farmers in water stress
Time
e.g., multi-scalar modes of interaction in managed groundwater systems (redrawn from Castilla-Rho et al. 2015)
e.g., groundwater depletion embedded in international food trade (Dalin et al. 2017)
e.g., social adoption of civil society and state efforts to promote groundwater recharge (Patel et al. 2020)
e.g., drawdown across farmers' wells across alternative regulation scenarios (Castilla-Rho et al. 2015)

Figure 2: Groundwater-connected systems are social-ecological systems. a) Mapping a regional environment's groundwater-connected systems to elements of the social-ecological systems framework (shown in b). b) The social-ecological systems framework, redrawn from McGinnis and Ostrom (2014). c) Properties of groundwater-connected systems that reflect how these systems behave as complex adaptive systems, with examples from Castilla-Rho et al. (2015), Dalin et al. (2017), and Patel et al. (2020).

Box 1: Understanding the interactions and outcomes of 'dry wells and reduced rural water security' through the framing of groundwater-connected systems. For this example, we use the setting of California's Central Valley and use a narrative approach to weave in multiple perspectives, data sources and formats.

In California's Central Valley (CCV), groundwater pumping accelerates during times of drought (Liu et al. 2022), further depleting groundwater resources. As this occurs, wells across the state run dry (Jasechko and Perrone 2020).

> "The whole time you're going, 'Oh please, let it be something else. Let it be a switch. Let it be the pump — let it be anything but being out of water,'" a domestic well owner in California's Central Valley (Becker 2021).

The majority of groundwater withdrawal in the Central Valley occurs for agricultural irrigation, and the valley is one of the most agriculturally productive areas in the world. Simultaneously, tens of thousands of domestic wells provide rural water security across the state (Pauloo et al. 2020). While the conventional drivers of groundwater behaviour (e.g., geology, topography, and climate) remain important, the human fingerprint of groundwater pumping, climate change induced drought, and land use change are dominant drivers in this setting (*sensu* Abbott et al. 2019). Global processes also factor into this situation as the Valley is an exporter of virtual water (Marston and Konar 2017). Thus, multiple tensions exist in the Central valley, including but not limited to those between local water security and importing regions' food security, and between rural well owners and industrial agriculture regarding groundwater access.

> "We want to be at the table. I know we are little but we don't want to be left behind. We want to know what's going on". "What is your biggest problem? Farming? Who got all the control? Farmers. So good luck fixing the problem". "Who's representing the small people or the city or what not?". Excerpts from interviews conducted with rural community members in the Central Valley by Dobbin et al. (2020).

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 (Molle and Closas 2020; Villholth and Conti 2018). Despite the accelerating rate of groundwater depletion in the valley, placing the state's groundwater resources on pathways to sustainability has been a policy objective since the development and subsequent enactment of the Sustainable Groundwater Management Act. The Act's decentralised approach delegates the process of defining groundwater sustainability to local groundwater sustainability agencies, creating nested, context-based opportunities for managing groundwater. Yet, risks to rural water security may occur in locations where existing power and economic inequalities come to dominate this process. This is possible through the setting of management targets, often water table depths, that may be derived without engagement with rural, disadvantaged communities and that favour dominant, richer, and industrial users who are able to afford the drilling costs of deeper wells (Bostic et al. 2020). This process can thus entrench existing bias found in news print and science in favour of the interests of the agricultural industry, leaving interests of disadvantaged rural communities "underrepresented, understudied, and underserved" (Bernacchi et al. 2020; Fernandez-Bou et al. 2021).

> The Yocha DeHe Wintun Nation stewards over 40,000 acres in the Yolo Subbasin of the Sacramento Valley. On these lands, Yocha DeHe Wintun Nation practises both traditional food

cultivation and production agriculture. The Nation’s name, Yocha DeHe, translates to “home by the spring water” (Romero-Briones et al. 2020).

Simultaneously, falling water tables also place at risk groundwater-dependent ecosystems (GDEs) (Rohde et al. 2019), with estimates indicating nearly half of all GDEs in California have experienced declining groundwater levels (Rohde et al. 2021). Yet not only are the subterranean, terrestrial, and aquatic ecosystems placed at risk through groundwater depletion, but so too are the myriad set of ecosystem services and cultural values of GDEs (Kreamer et al. 2015). Thus, a focus on only human-groundwater relationships overlooks processes that link groundwater use with ecosystem health, and the feedback mechanisms that can impact humans through deteriorated ecosystem services provided by these GDEs. These GDE ecosystem services include services that directly support water security, such as water purification, increasing aquifer storage, and buffering hydrological extremes, and broader services that support social well-being including the cultural services associated with groundwater’s recreational, spiritual, religious, and aesthetic values (Gleeson et al. 2022).

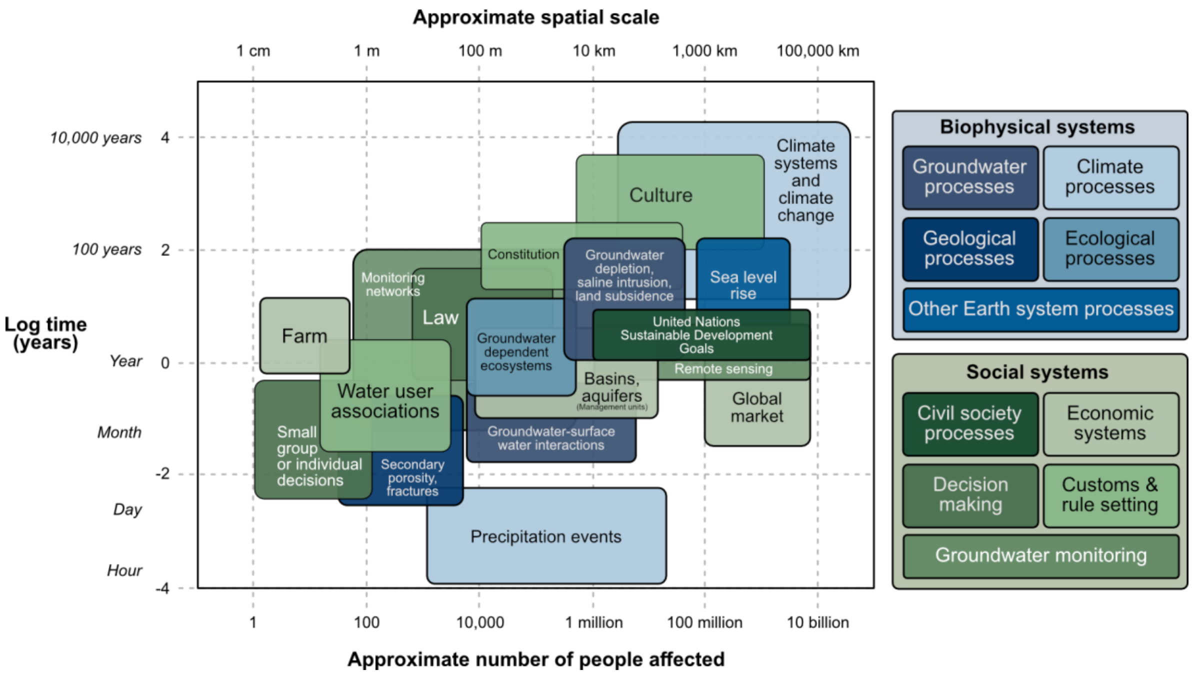

Figure 3: Spatial, temporal, and social scales of biophysical and social processes of groundwater-connected systems. The processes shown are not comprehensive but are intended to illustrate the diversity of processes across scales.

Invigorating groundwater sustainability with sustainability science

Groundwater sustainability, as a subdiscipline, lies at the intersection of groundwater science with sustainability science (see intersecting circles in Figure 1a). Sustainability science has blossomed over recent decades into a rich and robust literature (Table 1), yet our view is that groundwater topics have been underrepresented in sustainability science studies in contrast to other common pool resources such as forests and fisheries (Kajikawa et al. 2014). As social-ecological systems and their associated language and concepts permeate the sustainability science discourse, we see significant potential for greater application of sustainability science concepts to groundwater through the groundwater-connected systems framing. Doing so moves groundwater work towards increasingly interdisciplinary, relationship-centric, and complexity-based approaches (see arrow in Figure 1a).

To facilitate this, we provide below a brief sustainability science primer for hydrogeologists through a set of core sustainability science concepts: wicked problems, the multiple scales and dimensions of sustainability, and an introduction to analysis frameworks. Though this set of terms is limited, we view their collection as a minimum but representative set of introductory concepts alongside the key references provided in Table 1. We briefly summarise and connect these key concepts to our framing of groundwater-connected systems.

Wicked problems are problems with no single solution, where conflicting values and a variety of standpoints between partners, collaborators, and stakeholders lead to different situational understandings and desired outcomes (Lönngren and van Poeck 2021). Wicked problems are embedded in social-ecological systems where interactions among social, economic, and biophysical systems are poorly understood, highly variable, and can produce undesirable consequences from well-intentioned actions. Owing to these properties, wicked problems are not solved as much as they are continuously managed (DeFries and Nagendra 2017).

Whereas the physical sustainability of a groundwater system can be objectively defined through, for instance, a water balance, sustainability in groundwater-connected systems should be approached as a wicked problem. Drivers of groundwater depletion and misuse are complex and diverse (see Box 1), and the challenge of steering groundwater systems on pathways towards sustainability is well reflected in the literature (Aeschbach-Hertig and Gleeson 2012; Ostrom 1993; Zellner 2008; Zwarteveen et al. 2021). Important groundwater-connected processes occur across a wide range of spatial and temporal scales, which span well-head to catchment, aquifer, and transboundary domains, to the global scale; and across seasonal to century and longer time ranges (Figure 3). These interactions between processes of dramatically different spatial and temporal scales contribute to the “wicked” nature of sustainability in groundwater-connected systems.

Sustainability is a deeply normative concept and is tightly coupled to notions of justice (Wijsman and Berbés-Blázquez 2022; Jerneck et al. 2011). The contemporary concept of sustainability is rooted in the Brundtland Report's (1987) definition of sustainable development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Purvis et al. 2019). While this foundational definition concerned intergenerational equity, current definitions have expanded to also include considerations of equity across spatial and social dimensions (Jerneck et al. 2011). Thus, sustainability is a multidimensional concept expressed through determinations of what is equitable across generations (temporal dimension), regions (spatial dimension), and identities (socio-economic or cultural dimension). These determinations hinge on normative judgements of 'what should be' (Lélé and Norgaard 1996). Finding consensus in these discussions can be elusive with contested understandings of what goals should be pursued.

Sustainability focused and framed groundwater research is rapidly growing (Elshall et al. 2020), and application of sustainability science concepts are already present in the existing literature. Notable examples are increasingly expansive groundwater sustainability definitions (Gleeson et al. 2020), modelling and approaches that consider complex social and institutional dynamics (Castilla-Rho et al. 2015), and transdisciplinary approaches that directly engage groundwater users as research partners (Zwarteveen et al. 2021).

Applying sustainability science frameworks to groundwater sustainability topics is an important step to further align the literatures and can provide additional insights to better delineate the groundwater sustainability problem space, understand its complexity, and guide more effective and engaged work. A framework is the "most general form of conceptualization; [providing] checklists or building blocks for consideration in constructing theories or models" (Clark and Harley 2020). In our illustration of groundwater-connected systems as social-ecological systems (Figure 2), we used the Social-Ecological Systems Framework of (McGinnis and Ostrom 2014). Many other frameworks exist to study social-ecological systems. For a comparison of common frameworks, see Binder et al. (2013).

The groundwater-connected system framing does not call to replace existing definitions of physical groundwater sustainability. Instead, the framing provides additional considerations to apply alongside determinations of physical sustainability (Table 2). Physical sustainability therefore becomes a necessary but insufficient condition for broader social-ecological sustainability in groundwater-connected systems. These broader considerations can include equity of groundwater access across different user groups and communities, determination of ecological thresholds for groundwater use, identification of cultural sites that depend on groundwater, tracking of community participation and engagement levels in monitoring and management initiatives, and broader considerations of environmental justice. In applied settings, this could take the form of quantitative analysis, such as calculating horizontal inequality ratios (Boyce et al. 2016) for groundwater accessibility across user groups, tracking citizen science participation rates, or using satellite imaging to determine the proportion of a landscape whose terrestrial ecosystem thresholds for water table drawdown have been exceeded. Likewise, applied qualitative analysis could take the form of tracking community member perceptions of fairness in groundwater allocation decision making processes, sense of well-being in relation to the services and functions the local groundwater provides, or routine analysis and synthesis of community members perceptions of hydrological, ecological, and socio-economic change. These possible additions reflect the multi-objective nature of sustainability in groundwater-connected systems.

Table 2: Added considerations for groundwater sustainability through the application of the groundwater-connected systems framing.

Conventional considerations for groundwater sustainability	**Additional considerations for groundwater sustainability through the groundwater-connected system framing**
Flux based approaches: ● Recharge rate (Döll and Fiedler 2008) ● Mean renewal time (Bierkens and Wada 2019) ● Groundwater development stress (Alley et al. 2018) ● Water balance (Richey et al. 2015) ● Groundwater footprint (Gleeson et al. 2012) ● Environmental flow needs (de Graaf et al. 2019) Long-term goal setting and backcasting (Gleeson et al. 2012) Calls for equitable, inclusive, and long-term governance and adaptive management (Gleeson et al. 2020)	How do changes in groundwater quantity and quality lead to changes in ecosystem services? How does groundwater access change with trends in groundwater storage? Are impacts faced evenly across the affected population? Are access inequalities being formed or amplified? And, how do social and economic attributes affect people's ability to cope with changing groundwater quality and quantity? Are existing power and economic inequalities dominating groundwater governance processes? Are cultural values and other social relationships to groundwater acknowledged and valued in sustainability plans and management decisions? How are groundwater storage trends altering the Earth system? How are changes in Earth system components impacting local to regional scale groundwater resources, such as through altered rates and spatial patterns of groundwater recharge?

Wide applicability to groundwater science and beyond

The groundwater-connected systems framing does not provide an explicit roadmap to follow. Rather, we provide here a set of possible implications across the core domains of data collection efforts, scientific investigations, governance and management approaches, and education. Our aim is to provide an overview of the breadth of work we believe the groundwater-connected system framing can contribute to.

Implications for data collection

Empirical, grounded analysis of groundwater-connected systems requires observational data on the relationships that constitute these systems. The relevant data space to study groundwater-connected systems includes all social-ecological systems that interact with groundwater resources (e.g., Figure 2). Thus, this pertinent data space is more expansive and diverse in comparison to the data requirements for hydrogeological studies. These data can include conventional types of hydrogeological data, such as water table levels, but also extends to less traditional data such as the extent and type of groundwater-dependent ecosystems, governance, economic and social dimensions, including data on social norms, drivers of groundwater user behaviours, the effectiveness of rules, and community values in relation to groundwater. At present, little of this multi-dimensional data space is collected and shared.

Yet, this expanded delineation of relevant data for groundwater studies introduces data formats that do not easily integrate with the typical data workflows and numerical models of groundwater hydrologists. For example, dominant data types in the social sciences are in the form of qualitative case study outcomes, surveys, and interviews. There is a long list of applied environmental topics and research communities also navigating the challenges of integrating the social and natural sciences (Strang 2009; Hirsch Hadorn et al. 2010) for groundwater-connected systems to learn from and build on. While some notable groundwater studies do exist that integrate multiple data formats (e.g., Castilla-Rho et al. 2017), the enduring challenge remains to integrate data while preserving the subtlety and fidelity of each data format (Pooley et al. 2014). Noting that social sciences often face situations of reduced power and influence when in collaboration with natural scientists (MacMynowski 2007), great care and methodological attention is needed to ensure that social science data is not "compressed into extinction" (Strang 2009, Pooley et al. 2014). To accomplish this requires significant amounts of time dedicated to understanding the different research philosophies and methods used among interdisciplinary collaborators, which can help avoid collaborative work from only using data that integrates easily with the methods of the dominant discipline (Strang 2009).

Pursuing more comprehensive data collection is accompanied by the additional need to synthesise such efforts via open access initiatives. This call to collect more diverse data requires careful consideration of what data is not only practical but ethical to obtain and share. Zipper et al. (2019) provide guidance in navigating the open science-data privacy dilemma in socio-hydrology, which can also apply to groundwater-connected systems data.

One opportunity to address data deficiencies is to embrace the potential of community or citizen science (Buytaert et al. 2014) and other forms of community-based participatory research. Community science not only fills observation deficiencies but also leads to increased social awareness around change in human-environmental systems (Kimura and Kinchy 2016). Thus, these initiatives are particularly relevant in regions where groundwater-connected systems are undergoing rapid change.

Implications for scientific investigations

As an overriding implication on scientific practice, the groundwater-connected systems framing forces a recognition of the role and influence of the researcher. This calls on researchers to examine the impact of their technical expertise and research philosophy on study design and outcome. The groundwater-connected systems framing thus challenges the conventional view in the natural sciences of doing “good” science while holding no opinions and urges against claims of objectivity in study outcomes.

To facilitate this reflexivity, greater focus needs to be placed on documenting conceptual models in these higher-dimensional, more complex studies. Doing so not only aids in identifying the strengths of a given approach but also explicitly highlights the processes considered and omitted from representation, the limitations of these decisions, and the uncertainties they introduce. Documenting limitations and uncertainty does not undermine a study’s value but rather is a core research output that aids in locating knowledge gaps and informing subsequent work (Wagener et al. 2021). Such clarification requires stating and justifying assumptions underpinning analyses. This focus on uncovering assumptions is consistent with recent calls in the groundwater modelling literature (“assumption hunting” in Peeters 2017) but extends across a wider, interdisciplinary domain for groundwater-connected systems. Furthermore, this methodological introspection can facilitate more effective collaborations by increasing mutual understanding across disciplines (Strang 2009).

To address uncertainty given stark structural differences between models, the method of multiple working hypotheses via an ensemble-of-models approach is already being used in the groundwater and hydrological modelling communities (Clark et al. 2011; MacMillan 2017). This many-model paradigm can lead to wiser choices, more accurate predictions, and better constrained uncertainty. Ensemble-of-model approaches should be pursued for topics concerning groundwater-connected systems which are characterised by less process understanding and greater uncertainty relative to physical groundwater systems. This approach does not need to take any particular form and can be used to integrate methodologically diverse studies, each fit for a specific purpose, to identify common outcomes and areas of convergence and divergence (Castilla-Rho et al. 2020).

Research on groundwater-connected systems necessarily must focus on the relationships and interactions between system components rather than on groundwater in isolation. Such research often aims to identify complex system attributes and behaviours (e.g., Figure 2c). For instance, methods to detect early-warning signals for regime shifts in complex systems (Scheffer et al. 2009) are only just beginning to be applied to groundwater-connected systems (e.g., Zipper et al. 2022). Alternatively, the heterogeneity of groundwater-connected systems requires that actions to promote sustainability in these systems fit the local context. For example, studies (e.g., Richard-Ferroudji et al. 2018, Ulibarri et al. 2020) that identify the combination of socio-economic, institutional, infrastructural, and hydrogeological conditions that lead to successful implementation of managed aquifer recharge projects are a useful advance beyond conventional feasibility studies that focus exclusively on the physical system and setting. Lastly, quantitative studies that identify macro-level conditions that characterise a social-ecological system's composite state or behaviour can be found in the broader social-ecological literature (Williamson et al. 2018; Leslie et al. 2015) but have yet to be adapted for groundwater-connected systems.

The groundwater-connected systems framing also creates space for greater adoption of community-based participatory research that enables data and knowledge co-production in transdisciplinary settings. Such knowledge co-production can facilitate the integration of multiple knowledge bases and can help ensure that research better reflects local partner and stakeholder values and relationships with groundwater. Simultaneously, community-based participatory research strengthens scientific practice and output by canvassing a larger evidence base to inform studies (*sensu* Tengö et al. 2014). These transdisciplinary interactions between academics and stakeholders can create synergistic interactions across knowledge systems and worldviews (Castilla-Rho et al. 2020).

Implications for governance and management

Shifting from a resource-centric to a social-ecological systems approach can avoid traditional tendencies of disconnecting groundwater resources from their social context. Doing so rejects the types of simplistic and uniform thinking that has led to failed top-down, technical and one-size--fits-all governance designs (Villholth and Conti 2018). Instead, the social-ecological systems lens recognizes 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).

Complex adaptive systems provide an alternative paradigm to equilibrium-based approaches and support the linking of adaptive management and participatory modelling processes (Crevier and Parrott 2019). Such adaptive management needs 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, and multi-scalar objectives such as downscaled planetary boundaries (Zipper et al. 2020). However, global and downscaled objectives require reconciling with place-based values, preferences, and norms. Thus, the pursuit of bottom-up approaches that can include self-regulation or peer-to-peer monitoring that also fit within broader multi-scalar sustainability goals is a grand challenge for governance in groundwater-connected systems.

Underrepresentation of groundwater in global sustainability initiatives limits such multi-scalar approaches. Most notably, groundwater is largely absent from the Sustainable Development Goals (Gleeson et al. 2020) despite being connected to nearly half of the initiative’s targets (Guppy et al. 2018). The framing of groundwater-connected systems supports the consideration and thus inclusion of groundwater in such interdisciplinary, multi-objective initiatives and helps confront the overlooked and invisible history of groundwater in policy discourses.

Other works calling for social-ecological approaches to groundwater elaborate more extensively on management implications. See Bouchet et al. (2019) for a discussion on strategic adaptive groundwater management, and Barreteau et al. (2016) for a description of an integrated groundwater management landscape across water, land, and energy sectors.

Implications for education, training, and communication

Groundwater-connected systems span conventional academic disciplines and require different skill sets than those used in traditional, discipline-specific groundwater work. This discipline spanning is common across sustainability science and challenges conventional education pathways. Fruitful uptake and implementation of the groundwater-connected system framing will rely on its incorporation into the training of groundwater academics, practitioners, policy makers, users and stakeholders. Below we highlight how the framing can interface with education at the undergraduate and graduate levels, to existing professionals, and in science communication efforts.

As it is crucial to develop a strong disciplinary foundation, we do not advocate for any fundamental changes to training at the undergraduate level. Yet, in such disciplinary programs, we believe it is possible and important to expose students to core concepts of sustainability science at an introductory level. Doing so fosters an awareness of the interdisciplinarity and complexity of groundwater-connected systems and underscores the need for disciplinary specialists to participate in diverse teams when identifying and solving problems in applied settings. In our own teaching of upper-year civil engineering courses on water sustainability and groundwater hydrology (Huggins and Gleeson 2022), we have begun introducing sustainability science fundamentals, including the ‘threshold concepts’ of sustainability science (Loring 2020), through applied case examples and in class activities. These are often tied to multimedia resources such as the Water Underground Talks (https://www.waterundergroundtalks.org/), an initiative that shares short interviews and research talks on groundwater connections to climate, food, and people.

We perceive graduate school as the appropriate level for more rigorous application of the concepts discussed in this paper. There is already a rich global ecosystem of graduate programs, schools, and research institutes that focus on social-ecological systems, resilience, and complex adaptive systems (e.g., the Stockholm Resilience Centre, the Centre for Sustainability Transitions, the Ashoka Trust for Research in Ecology and the Environment). Yet, we perceive potential for the graduate course and research theses conducted at these institutes to place additional focus on groundwater. The groundwater-connected system framing can be used to facilitate this conceptual connection between groundwater and social-ecological systems education and research.

There is also a need for professional training and development initiatives to introduce professionals to the framing of groundwater-connected systems. These could include practitioner-focused seminars; online guides to groundwater-connected systems concepts, methods, and data; and interactive workshops that could use agent-based models or serious games (e.g., Ouariachi et al. 2018) that would enable participants to grapple with complexity, adaptation, feedback mechanisms, and uncertainty in a risk-free environment while gaining practice working in inter- and transdisciplinary teams.

Finally, the framing of groundwater-connected systems can be a powerful tool to build public awareness on the importance of groundwater in everyday life and sustainable, equitable futures. While groundwater is often ‘advertised’ to the public based on impressive statistics (e.g., as the world’s largest store of unfrozen freshwater), we perceive that few aside from groundwater hydrologists will find interest in groundwater presented this way amid global pandemics, armed conflicts, and social movements. With the same motivation as the groundwater-connected systems framing, we argue that we should present groundwater in a more relational way. Presenting groundwater in relatable narratives is a compelling and effective way to increase public interest in groundwater. One way to do this is by telling stories about the ways people are connected to groundwater, such as through the food we eat, the activities we enjoy and find important, such as swimming or ceremonies, among other social and cultural relationships to groundwater.

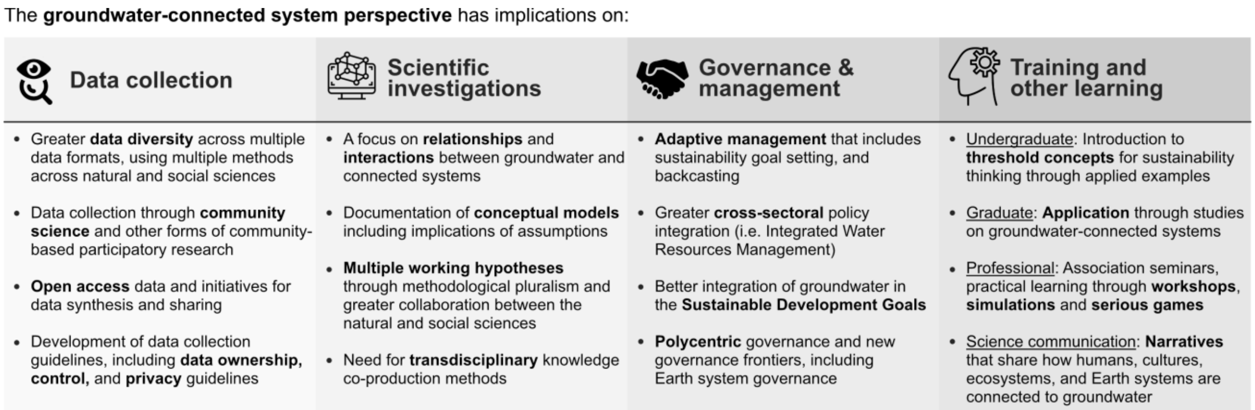

Figure 4: Implications of the groundwater-connected systems framing on data collection, scientific investigations, governance and management approaches, and education, training, and communication.

Conclusion

Groundwater-connected systems are formed by social, economic, ecological, and Earth system interactions with physical groundwater systems. We present the framing of groundwater-connected systems to facilitate greater representation of these interactions in groundwater research and practice through data collection, scientific investigations, governance, management, and education. However, the framing does not provide a specific blueprint for all to follow. Rather, we present this framing as an invitation to the groundwater community to revisit foundational concepts and explore a wide set of methods that can be used to advance groundwater science and sustainability in diverse hydrogeological, social, and ecological contexts. The groundwater-connected systems framing can provide a useful basis for growth and collaboration within the groundwater community. Equally, the framing is an invitation to other disciplines and the social-ecological research community at large to join us in advancing this uncertain, complex, and needed research on groundwater connections and sustainability in social-ecological systems.

[end of main text]

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: T.G. and J.C.R., Figure 3 from: 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

We would like to thank Leonard Konikow, Charles Andrews, and four anonymous reviewers for their comments and suggestions that helped improve the quality of the manuscript.

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 2 was produced by modifying and assembling individual vector symbols from the Integration and Application Network (ian.umces.edu/media-library), licensed under CC BY-SA 4.0. Authors 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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Supporting information

Additional Supporting Information may be found in the online version of this article:

Supporting Text. An extended description of Figure 2a.

Table S1. Common principles of complex adaptive systems found in groundwater-connected systems.

Supporting Information is *not* peer reviewed.

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List of figure, table, and box captions

[listed in the order they appear in the text]

Figure 1. Groundwater groundwater-connected systems as a framing for groundwater practice and research. (a) We argue that groundwater investigations and assessments should increasingly move from disciplinary pursuits focusing on physical groundwater systems to inter- and transdisciplinary collaborations that focus on understanding groundwater interactions and functions in larger connected systems. (b) This new framing is enabled by understanding groundwater-connected systems as social-ecological systems, which introduces new methods or amplifies existing methods for data collection, research, governance and management approaches, and education. To support interpretation of this figure, consult the yellow text boxes in their numbered order.

Table 1: Summary of terminology used in this paper.

Figure 2: Groundwater-connected systems are social-ecological systems. a) Mapping a regional environment's groundwater-connected systems to elements of the social-ecological systems framework (shown in b). b) The social-ecological systems framework, redrawn from McGinnis and Ostrom (2014). c) Properties of groundwater-connected systems that reflect how these systems behave as complex adaptive systems, with examples from Castilla-Rho et al. (2015), Dalin et al. (2017), and Patel et al. (2020).

Box 1: Understanding the interactions and outcomes of 'dry wells and reduced rural water security' through the framing of groundwater-connected systems. For this example, we use the setting of California's Central Valley and use a narrative approach to weave in multiple perspectives, data sources and formats.

Figure 3: Spatial, temporal, and social scales of biophysical and social processes of groundwater-connected systems. The processes shown are not comprehensive but are intended to illustrate the diversity of processes across scales.

Table 2: Added considerations for groundwater sustainability through the application of the groundwater-connected systems framing.

Figure 4: Implications of the groundwater-connected systems framing on data collection, scientific investigations, governance and management approaches, and education, training, and communication.