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Groundwater connections and sustainability in social-ecological systems

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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 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 are social-ecological systems where interactions lead to complex behaviours such as feedbacks, non-linear processes, multiple stable system states, and path dependency. These complex behaviours are only visible through this integrated systems framing and are not endogenous properties of physical groundwater systems. This framing is syncretic as it aims to provide a common conceptual foundation for the growing disciplines of socio-hydrogeology and eco-hydrogeology. This framing also facilitates better alignment of the groundwater sustainability discourse with emerging sustainability concepts and principles. Doing so provides an understanding of groundwater sustainability as not a state to be reached but rather a challenge characterised by multi-faceted values and preferences that require place-based specification and adaptive management. The groundwater-connected systems 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?

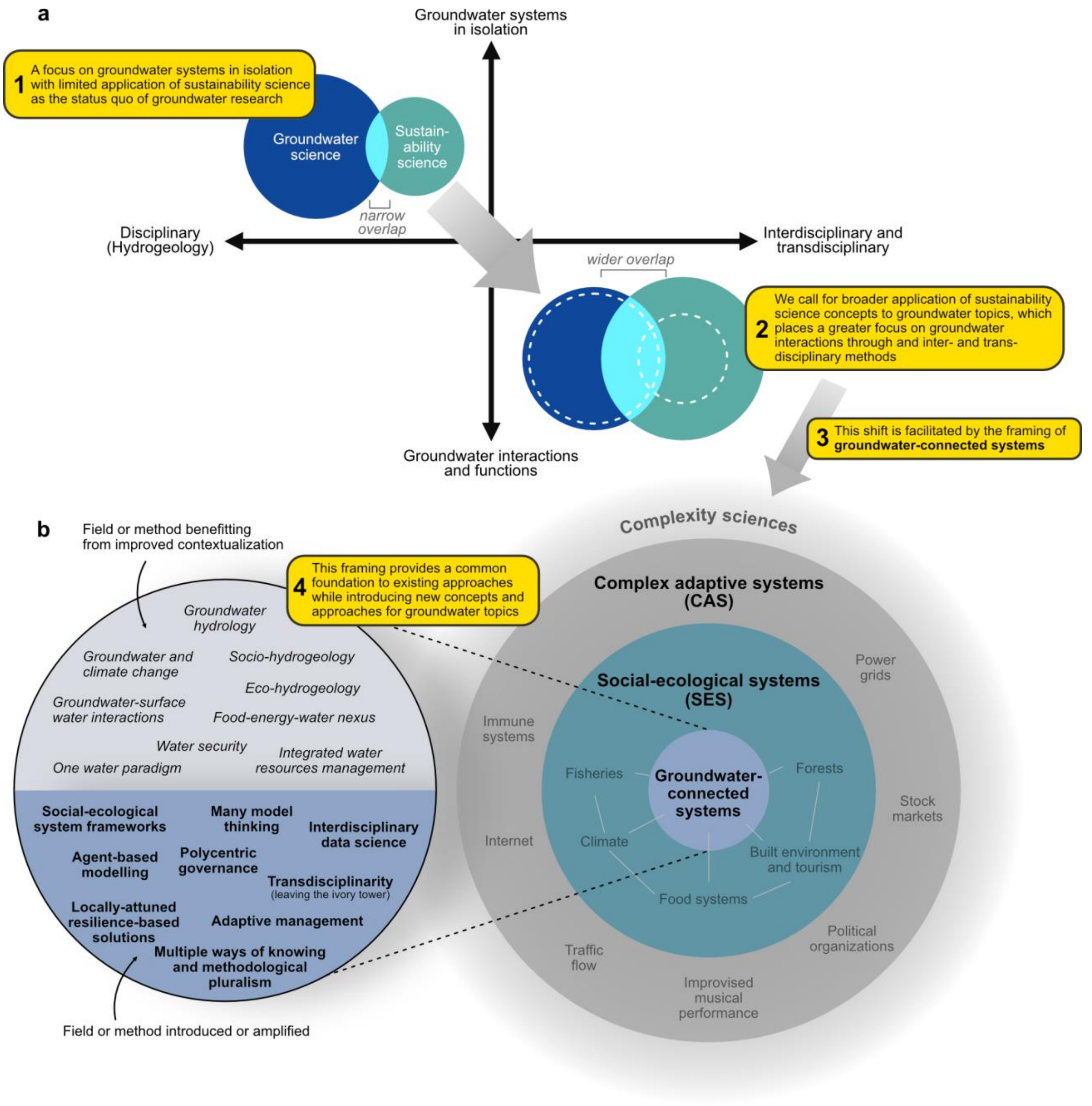
Amid calls for innovation in groundwater research, substantial progress has been made to document groundwater interactions and relationships in social, ecological, and Earth systems through the emerging disciplines of socio-hydrogeology (Re 2015), eco-hydrogeology (Cantonati et al. 2020), groundwater in Earth systems science (Gleeson et al. 2020), and through transdisciplinary methods (Zwarteveen et al. 2021). 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 shifts 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).

Our intention for the framing is to facilitate novel, methodologically pluralistic work in groundwater that can produce outputs more aligned to 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 in doing so, support 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 of groundwater-connected systems can impart on data collection, scientific investigations, governance and management, and education in '*Wide applicability to groundwater science and beyond*'. Key terms used in this paper are defined in Table 1.



1 A focus on groundwater systems in isolation with limited application of sustainability science as the status quo of groundwater research

2 We call for broader application of sustainability science concepts to groundwater topics, which places a greater focus on groundwater interactions through and inter- and trans-disciplinary methods

3 This shift is facilitated by the framing of **groundwater-connected systems**

4 This framing provides a common foundation to existing approaches while introducing new concepts and approaches for groundwater topics

Figure 1. Groundwater groundwater-connected systems as a new 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 complex systems. (b) This new framing is enabled by understanding groundwater-connected systems as social-ecological systems, which introduces or amplifies new 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 other 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	Berkes and Folke (1998) Ostrom (2009) ● Colding and Barthel (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 can take many forms. Groundwater irrigated agriculture, domestic well owner's water security, and other social relations to groundwater such as 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 examples include groundwater-aquatic biodiversity relationships such as ecological responses to transgressed environmental flow requirements or terrestrial groundwater-dependent ecosystems. Groundwater-connected systems can also be the network of interactions between these often intertwined systems.

We understand groundwater-connected systems to be 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). Thus, 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 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. This framing is critical as it enables the field to use myriad paradigms, perspectives, models, and methods from the social-ecological literature that are currently absent or underutilised for groundwater topics.

In Figure 2a, we present a conceptual diagram of groundwater-connected systems as social-ecological systems. For this illustration, we rely on the predominant framework used to study social-ecological systems: the social-ecological systems framework (Partelow 2018; McGinnis and Ostrom 2014; Figure 2b). Using this generic environment, we associate features and processes of groundwater-connected systems to elements of the social-ecological system framework. These attributions are indicative of the conceptual alignment between groundwater-connected systems and social-ecological systems and are not comprehensive. For an extended description of Figure 2a, see the Supporting Information.

Interactions and feedbacks in social-ecological systems occur across a multiple of space and time scales and constitute a core consideration of social-ecological systems analysis. An example of cross-scalar interactions in groundwater-connected systems includes the relationship between international food trade, groundwater depletion, and environmental flows. International food trade networks drive groundwater depletion (Dalin et al. 2017) that manifests as local to regional scale drawdown of the water table. When the water table drops, it can have cascading impacts on aquatic ecosystems that depend on groundwater discharge. For example, environmental flow transgressions driven by a loss of groundwater discharge can lead to local-scale impacts on fish populations, aquatic ecologies, and riparian vegetation (Gleeson and Richter 2017). 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.

In the groundwater literature, many of these interactions and outcomes remain undocumented, excluded, or under-analysed. The outcomes from these interactions in groundwater-connected systems concern water, food, and energy security, biosphere integrity and planetary health, cultural values, social equity, and Earth system stability (as identified under ‘Outcomes’ in Figure 2a). While these outcomes are often included in discussion sections as context for hydrogeological studies, they are rarely modelled or explicitly considered in analysis. These relationships and outcomes become the explicit focus for analysis of groundwater-connected systems.

The groundwater-connected systems framing can help generate narratives and construct hypotheses of causal mechanisms in complex systems. To illustrate this potential to facilitate more systematic, holistic problem understanding, we use an example outcome from Figure 2a: *‘wells running dry and reduced water security*’, in Box 1.

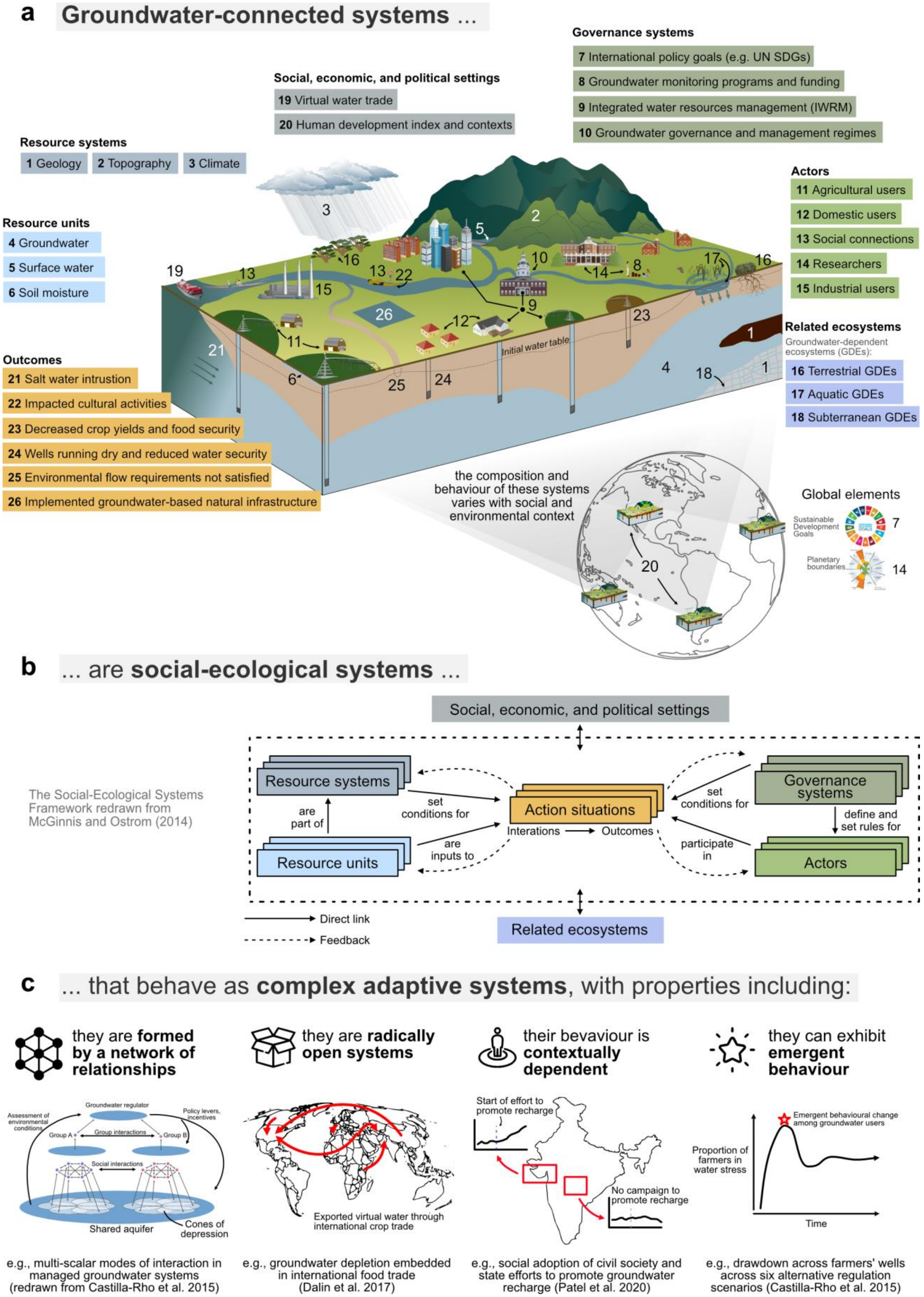

a
Groundwater-connected systems ...
Governance systems
7 International policy goals (e.g. UN SDGs)
8 Groundwater monitoring programs and funding
9 Integrated water resources management (IWRM)
10 Groundwater governance and management regimes
Social, economic, and political settings
19 Virtual water trade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

Potential causal mechanisms of falling water tables include the conventional drivers of groundwater behaviour: geology, topography, and climate in conjunction with human activity. Human activity drivers include direct impacts such as pumping for agricultural irrigation or land use change, and indirect impacts such as climate change that alters regional precipitation and evapotranspiration patterns. 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 (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 and regulation 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 subsidisation (Scott and Shah 2004). Insufficient groundwater monitoring programs, infrastructure, and funding undermine the anticipatory capacity of both well owners and governments. Just as importantly, impacts can also be more holistically considered through the groundwater-connected systems approach. The ability to adapt to groundwater trends will differ based on the wealth of well-owners as only the wealthy will be able to drill deeper wells to keep pace with falling groundwater levels (Perrone and Jasechko 2019). This ability to amplify existing economic inequalities is one possible cascading impact of groundwater depletion. Alternatively, when groundwater depletion occurs in proximity to connected surface water bodies or terrestrial groundwater-dependent ecosystems, these interactions can lead to transgressed environmental flows and degraded groundwater-dependent ecosystems. The harms imposed on cultures and other social relations to these water bodies and their ecologies, such as their role in ceremony, as a source for cultural identity, or for recreational purposes (Anderson et al. 2019) represent a second set of potential cascading impacts.

Our framing of groundwater-connected systems is syncretic in that it aspires to tie together and build on emerging trends in groundwater-related disciplines. These include an increase in interdisciplinarity (Barthel and Seidl 2017), a focus on social complexity and transdisciplinary collaborations (Re 2021), participatory modelling (Castilla-Rho et al. 2020), advocacy models (Ferré 2017), resilience frameworks (Hera-Portillo et al. 2021; Varis et al. 2019), transdisciplinary governance initiatives (Zwarteveen et al. 2021), and studies documenting ecological functions of groundwater including: groundwater-dependent ecosystems (Kløve et al. 2011), environmental flow contributions (Gleeson and Richter 2018), and interaction with plant rooting depth (Fan et al. 2017) among many other eco-hydrogeological interactions (e.g., Hose and Stumpp 2019; Lundgren et al. 2021). These developments overview the growth of socio-hydrogeology and eco-hydrogeology and, in our view, can all be considered through our framing of groundwater-connected systems. Viewing these various research trends through the common foundation of groundwater-connected systems can be a powerful step to facilitate greater awareness, dialogue, and collaboration between these research communities.

We note that existing work approaches groundwater from a social-ecological system perspective. These include studies on using interactions between groundwater user behaviours, social norms, and physical groundwater dynamics to establish rules for more sustainable groundwater management (Hammani et al. 2009), socio-historical studies on the social and political contexts that lead to successful implementation of managed aquifer recharge projects (Richard-Ferroudji et al. 2018), evaluations of the effect and timing of initiatives to promote groundwater recharge (Patel et al. 2020), and on general design principles for self-sustaining irrigation institutions (Ostrom 1993). Thus, we are far from the first to recognize the potential for social-ecological concepts to be applied to groundwater topics (Barreteau et al. 2016) and to the groundwater sustainability discourse (Bouchet et al. 2019). 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.

Specific benefits of our framing, in comparison to other calls to consider groundwater within larger social-ecological systems, are its direct applicability and enrichment of the groundwater sustainability discourse, its ability to facilitate further integration of sustainability science concepts into the study of groundwater as a social-ecological resource, and its even treatment and potential across the multiple dimensions of the groundwater sustainability problem space (i.e., to data collection, scientific investigations, governance and management, and education). The remainder of this paper is allocated to discussing these benefits and implications.

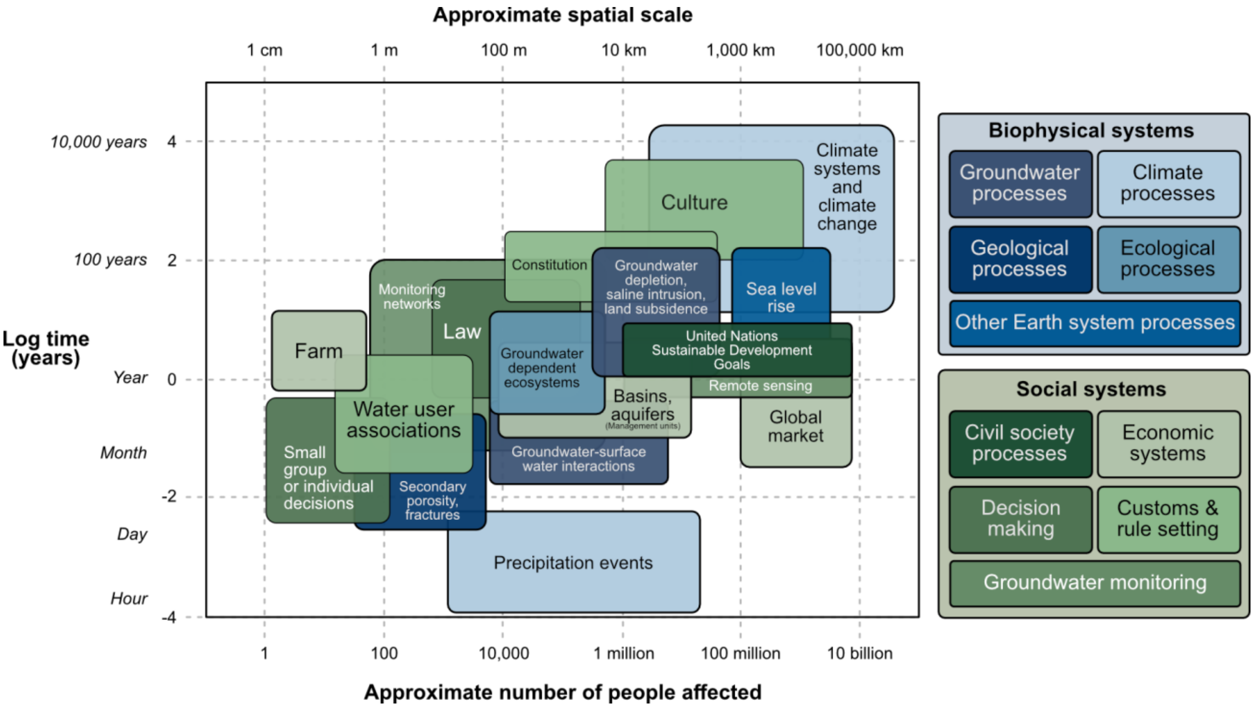


Figure 3: Spatial, temporal, and social scales of biophysical and social processes of groundwater-connected systems. The processes shown are meant to illustrate the diversity of processes across scales and are not comprehensive.

Invigorating groundwater sustainability with sustainability science

As groundwater science is central to guiding the groundwater sustainability discourse, the groundwater-connected systems framing has many direct implications for work addressing groundwater sustainability topics. We also recognize the broader applicability of the framing, which we discuss in the section '*Wide applicability to groundwater science and beyond*'.

Groundwater sustainability work 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). Thus, we see significant potential for greater application of sustainability science concepts to groundwater. Doing so moves groundwater work towards increasingly interdisciplinary, relationship-centric, and complexity-based approaches (see arrow in Figure 1a).

Key concepts that permeate the sustainability science discourse are wicked problems, the multiple scales and dimensions of sustainability, and analysis frameworks. Though this set of terms is limited, we view their collection as a minimum but representative set of introductory concepts for hydrogeologists. Below, we briefly summarise and connect these key concepts to our framing of groundwater-connected systems.

Wicked problems (Table 1) are problems with no single solution where conflicting values and a variety of standpoints between partners, collaborators, and stakeholders lead to different understandings of the problem being addressed and different preferences regarding 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. Because of the ambiguity that mires wicked problems, they 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 of groundwater-connected systems should be approached as wicked problems. 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, as a result, 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 (local), 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 represent one basis for the “wicked” nature of sustainability in groundwater-connected systems.

A second basis for viewing sustainability in groundwater-connected systems as a wicked problem is the multi-dimensionality of contemporary sustainability definitions. Sustainability theory is rooted in the question of what the present generation “owes” to future generations. However, current sustainability definitions extend beyond strictly intergenerational equity considerations to include dimensions of space and social identity (i.e., the responsibility of one region to another, and of one social or socio-economic group to another). Thus, sustainability is at minimum a three-dimensional concept (i.e., equity across time, space, and identity; Jerneck et al. 2011). This understanding of sustainability is therefore rooted in justice considerations (Wijsman and Berbés-Blázquez 2022) and such deliberations on justice are mired in subjective, normative judgements on ‘what should be’ (Lélé and Norgaard 1996). Finding consensus in these normative discussions is elusive, and such opaque understanding on what goals should be pursued is a core property of wicked problems.

The groundwater-connected system framing does not call to replace existing definitions of physical groundwater sustainability. Instead, the framing provides additional considerations to extend beyond determinations of physical sustainability (Table 2). Physical sustainability therefore becomes a necessary but insufficient condition for sustainability in groundwater-connected systems. Added considerations facilitated through the groundwater-connected system framing include equity of groundwater access, ecological responses and impacted ecosystem services, consideration of dynamic boundary conditions for physical sustainability (e.g., through land use change and climate change), and environmental justice dimensions (Table 2). These added considerations reinforce the idea that groundwater sustainability is not a system state that is 'achieved' but rather a multi-faceted set of values and preferences that require place-based specification and adaptive, continual management. Thus, the groundwater-connected systems framing adds considerations that support approaching groundwater sustainability as a multi-dimensional problem space and as a wicked problem.

Sustainability focused 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 two 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).

Table 2: Extending groundwater sustainability considerations through our framing of groundwater-connected systems.

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 are ecological functions affected by changes in groundwater storage? Do changes in groundwater quantity and quality lead to changes in ecosystem resilience? How does ecological change lead to altered ecosystem services? How does groundwater accessibility change with changes in groundwater storage? Are impacts faced evenly across the affected population or are access inequalities being formed? How does socio-economic context affect people’s ability to cope with changing groundwater quality and quantity? Are existing socio-economic inequalities being amplified, such as through reliance on groundwater for livelihoods? How are groundwater storage trends changing Earth system functions? What is the equitable local limit to groundwater use that scales to global sustainability frameworks and initiatives, such as the Sustainable Development Goals and the freshwater planetary boundary? How are trends in groundwater quality and quantity affecting social relationships to groundwater, including cultural values and services?

Wide applicability to groundwater science and beyond

Our framing of groundwater-connected systems does not provide an explicit roadmap to follow. Rather, we provide here a set of ideas across core domains of the groundwater sustainability solution space: data collection efforts, scientific investigations, governance and management approaches, and education. Our aim is to provide a sketch of the breadth of work we believe the framing of groundwater-connected systems can inspire and to nudge readers towards considerations of their own.

Implications for data collection

The pertinent data space to study groundwater-connected systems contains hydrogeological data (such as aquifer properties and water table observations) but also includes data representations across all elements of the social-ecological system (see elements in Figure 2b). These can include groundwater-dependent ecosystems and their responses to groundwater dynamics, as well as governance, economic and social dimensions (e.g., social norms, drivers of groundwater user behaviours, the effectiveness of rules, community values in relation to groundwater, etc.). At present, little of this multi-dimensional data space is collected and shared in hydrogeological studies.

As this pertinent data space is more expansive in comparison to the analogous data space for hydrogeological studies, it requires that more diverse forms of data are collected. However, this expanded data space simultaneously provides an opportunity to integrate existing data from other research fields. For instance, Lindersson et al. (2020) synthesise existing data sets for socio-hydrological studies. This work provides both an existing resource (as useful data between socio-hydrological and groundwater-connected systems topics overlap) and a source of inspiration to develop a specific synthesis of data sets for groundwater-connected systems. Such a synthesis would implicitly identify less-documented dimensions of groundwater-connected systems which could guide priority setting in future data collection efforts.

Yet, there is not only a need to accelerate more comprehensive data collection efforts but to also 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. Community science and the related approach of community-based participatory research are discussed more in '*Implications for scientific investigations*'.

One way to advance and consolidate more diverse data collection efforts can be to adopt the concept of "essential variables". Essential variables have been identified for the climate (i.e., the Global Climate Observing System's Essential Climate Variables), as well as for biodiversity, oceans, and ecosystem services (Balvanera et al. 2022). Developing a standardised set of essential groundwater-connected system variables could be used to explicitly delineate the pertinent data space's boundaries and to guide monitoring programs. Furthermore, a standard set of variables would allow for collection efforts at the scale of specific aquifers or jurisdictions to be synthesised and compared between regions and aggregated to larger scales.

Implications for scientific investigations

Approaching groundwater sustainability through the lens of groundwater-connected systems reframes issues, fundamentally, as transdisciplinary, complex system challenges. The complexity of groundwater-connected systems forces a recognition of the role and influence of researchers in study design. This calls on researchers to place even greater attention on contextualising their work as a product of their technical expertise, specific focus of each study, and to shy away from claims of objectivity in study outcomes. Thus, at a fundamental level, the groundwater-connected systems framing challenges the perception of doing good science while holding no opinions.

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 model, but also explicitly highlights the processes considered and omitted from representation, the limitations of these decisions, and the uncertainties they introduce. As Wagener et al. (2021) argue, 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. 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.

To address uncertainty given stark structural differences between models, the method of multiple working hypotheses via an ensemble-of-models (or 'multi-modelling') approach is already being advocated for and 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, better constrained uncertainty, and more robust designs. 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. Multi-modelling 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). Furthermore, multi-modelling as a practice better reflects the multiple partial perspectives that characterise sustainability discourses, where a sustainability-related challenge does not possess a single optimal solution but rather a multiplicity of partial perspectives and solutions that require reconciling.

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 2b). 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 (Zipper et al. 2022).

The heterogeneity of interactions in groundwater-connected systems requires that actions to promote groundwater sustainability be contextually appropriate. Studies that identify macro-level conditions that characterise a social-ecological system's state or behaviour (Williamson et al. 2018; Leslie et al. 2015) have yet to be adapted for groundwater topics. This form of analysis could be particularly useful to identify sustainability actions in groundwater-connected systems. For instance, using the example of managed aquifer recharge, one could ask: what are the social, economic, governance, political, and hydrogeological conditions that are most common in successful implementations of managed aquifer recharge projects? Assessments like this would be useful to move the discourse on groundwater sustainability initiatives and infrastructure away from suitability analyses that consider exclusively physiographic factors and towards assessments that consider contextual factors that span the social-ecological system.

The groundwater-connected systems frame also creates space for greater adoption of community-based participatory research that enables 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 respect to groundwater. Simultaneously, community-based participatory research strengthens scientific practice and output by canvassing a larger evidence base to inform studies (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). Yet, as we argue here, making such interactions fruitful demands entirely different skill sets to those used in traditional, discipline-specific groundwater research.

Implications for governance and management

Shifting from resource-centric thinking 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). This perspective also emboldens calls for regulatory approaches to be informed by and align with the unique physical characteristics of groundwater (Curran et al. 2022).

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 downscaling the planetary boundaries (Zipper et al. 2020). Global and downscaled objectives however 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.

Yet, groundwater is underrepresented in many global sustainability initiatives. 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 (IGM-scape) to inform management across water, land, and energy sectors.

Implications for education, training, and communication

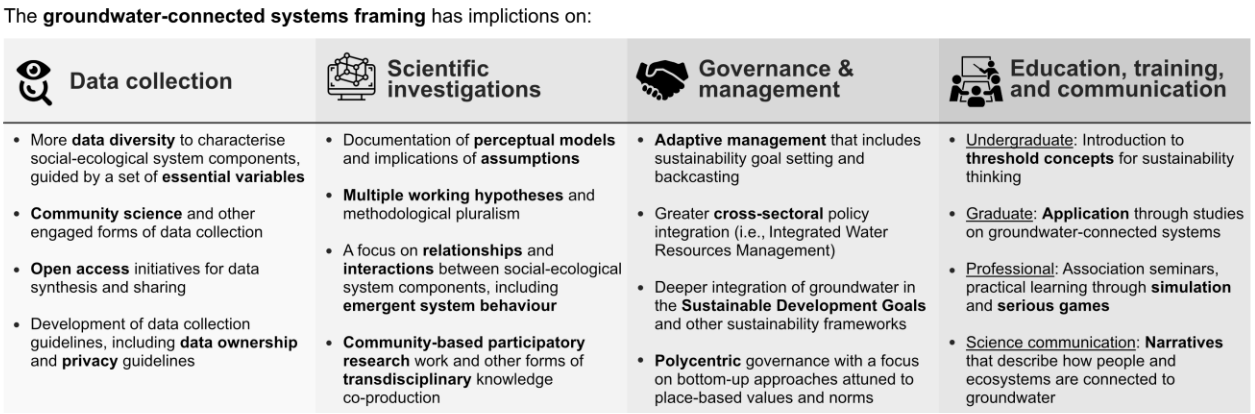
Groundwater-connected systems span conventional academic disciplines and require different skill sets than those used in traditional, discipline-specific groundwater work. This discipline spanning is common across sustainability science, which has been described as 'undisciplinary' (Robinson 2008). This undisciplinary science, defined as a "problem-based, integrative, interactive, emergent, [and] reflexive … [that involves] strong forms of collaboration and partnership" (Haider et al. 2018) challenges conventional education pathways. Yet, fruitful implementation of the groundwater-connected system frame will rely on greater exposure to the framing in 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 public-oriented science communication efforts.

At the undergraduate level, we believe it is crucial to develop a strong disciplinary foundation (e.g., in geology, geography, engineering, environmental sciences, etc.). However, we argue it is important to expose students in these disciplinary programs 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 problem solving. In our own teaching, we have begun introducing sustainability science fundamentals, including the 'threshold concepts' of sustainability science (Loring 2020), in upper-year civil engineering courses on water sustainability and groundwater hydrology (e.g., see lecture module "1.3 Sustainability Fundamentals for Groundwater Hydrologists", Huggins and Gleeson 2022). We reinforce these concepts using applied case examples in class activities that 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 the graduate-level to be 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 unfulfilled potential for the graduate course and research theses conducted at these institutes to place additional focus on groundwater. The groundwater-connected system frame 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 (Ouariachi et al. 2018) that would enable participants to grapple with complexity, adaptation, feedbacks, and uncertainty in a risk-free environment while gaining practice working in inter- and trans-disciplinary teams.

Finally, the framing of groundwater-connected systems can be a powerful tool to build increasing awareness and public interest 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 argue that few (aside from groundwater hydrologists) will have 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. 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 such as swimming, fishing, and ceremonies among other social relationships to groundwater processes. We believe presenting groundwater in relatable narratives is a more compelling and effective way to increase how the public cares about groundwater than on technical discussions of, for instance, drawdown rates, specific yield, and recharge.



The **groundwater-connected systems framing** has implictions on:

Data collection	Scientific investigations	Governance & management	Education, training, and communication
• More **data diversity** to characterise social-ecological system components, guided by a set of **essential variables** • **Community science** and other engaged forms of data collection • **Open access** initiatives for data synthesis and sharing • Development of data collection guidelines, including **data ownership** and **privacy** guidelines	• Documentation of **perceptual models** and implications of **assumptions** • **Multiple working hypotheses** and methodological pluralism • A focus on **relationships** and **interactions** between social-ecological system components, including **emergent system behaviour** • **Community-based participatory research** work and other forms of **transdisciplinary** knowledge co-production	• **Adaptive management** that includes sustainability goal setting and backcasting • Greater **cross-sectoral** policy integration (i.e., Integrated Water Resources Management) • Deeper integration of groundwater in the **Sustainable Development Goals** and other sustainability frameworks • **Polycentric** governance with a focus on bottom-up approaches attuned to place-based values and norms	• Undergraduate: Introduction to **threshold concepts** for sustainability thinking • Graduate: **Application** through studies on groundwater-connected systems • Professional: Association seminars, practical learning through **simulation** and **serious games** • Science communication: **Narratives** that describe how people and ecosystems are connected 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 systems that interact 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 is not intended to 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 tools and 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 focus on groundwater connections and sustainability in social-ecological systems.

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 3 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.

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List of figure, table, and box captions

Figure 1. Groundwater groundwater-connected systems as a new 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 complex systems. (b) This new framing is enabled by understanding groundwater-connected systems as social-ecological systems, which introduces or amplifies new 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.

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) Example 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).

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

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

Table 1: Summary of terminology used in this paper.

Table 2: Superimposing groundwater sustainability considerations facilitated through our framing of groundwater-connected systems with conventional considerations and approaches.

Box 1: A groundwater-connected system facilitated understanding of 'wells running dry and reduced water security'.