This is a non-peer reviewed preprint submitted to *EarthArXiv* and is currently under review.

The puzzling yet tractable diversity of global groundwater sustainability challenges

Xander Huggins [1-3]*, Tom Gleeson [4-5], James S. Famiglietti [6], Michele-Lee Moore [3,7], Karen Villholth [8]

[1] Institute for Resources, Environment and Sustainability, University of British Columbia, Vancouver, Canada
[2] High Meadows Environmental Institute, Princeton University, Princeton, USA
[3] Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden
[4] Department of Civil Engineering, University of Victoria, Victoria, Canada
[5] School of Earth and Ocean Sciences, University of Victoria, Victoria, Canada
[6] School of Sustainability, Arizona State University, Tempe, USA
[7] Department of Geography and Centre for Global Studies, University of Victoria, Victoria, Canada
[8] Water Cycle Innovation, Randers, Denmark

* Correspondence to xander.huggins@ubc.ca

Abstract

Global groundwater sustainability is a grand challenge that requires diverse approaches to account for local contexts. Yet, global groundwater assessments often focus solely on aggregate physical trends in storage, levels, and fluxes, overlooking the diversity of social-ecological functions provided by groundwater and their associated sustainability challenges. Here, we introduce *groundwater sustainability puzzles* as a concept and approach to identify distinct configurations of groundwater challenges within heterogeneous landscapes. Synthesizing 17 global datasets on groundwater functions and management problems, we map more than 200 puzzles worldwide, each representing a specific and spatially defined setting in which sustainability transformations must take root. Notably, half of global land area, population, and crop production situate within 20 or fewer puzzles respectively. This puzzle typology presents the most comprehensive assessment to date of the multi-dimensional composition of global groundwater challenges and offers a tool to facilitate cross-regional learning and network formation across similar contexts.

Introduction

There is broad agreement that groundwater management and governance should account for the complex, multidimensional, and place-based nature of the resource and its sustainability challenges[1–6]. A handful of geographically scattered regional descriptions help to highlight many of the nuances lost in a prevailing global discourse that often focuses on aggregate trends and statistics. In northern India, the proliferation of solar irrigation pumps is accelerating the rate of groundwater pumping and depletion[7]. Water managers grapple with the wicked challenge of curbing groundwater withdrawal rates while maintaining food production and water security[8] in a region where the burden of water scarcity has disproportionately fallen on the shoulders of women and girls and along class and caste lines[9]. In southern Spain, strawberries are irrigated with water pumped from hundreds of illegal wells[10]. The resulting groundwater depletion threatens the sensitive wetlands of Doñana national park, a UNESCO world heritage site home to a host of biodiversity, regionally endemic and threatened species, and an important ecological research station[11,12]. In western Canada, water use and warming temperatures have reduced summer low flows[13], threatening culturally significant salmon populations, while the settler-colonial government and Indigenous Peoples seek to establish better forms of water governance[14]. In the Guarani Aquifer System (Southern Brazil), one of the world's largest sandstone aquifers, large-scale clearing of subtropical forests and the conversion of pasturelands to intensive agriculture have strongly influenced local groundwater dynamics and threaten groundwater-dependent ecosystems[15]. Once seen as a global success story for transboundary aquifer governance, cooperation across the Guarani has slowed in recent decades[16]. In Jakarta, overpumping has caused severe land subsidence and continues to amplify the metropolis' vulnerability to saltwater intrusion and tidal flooding[17]. Herein, we are motivated by the questions: (1) Why should global depictions of global groundwater challenges better represent the diversity of regionally specific issues? (2) How might such representation be accomplished? (3) What are the benefits of advancing regionally disaggregated approaches to global groundwater sustainability science and management?

At the global scale, Famiglietti[18] has powerfully described the "*global groundwater crisis*" and many articles have described the state of global groundwater resources and their sustainability challenges[19–25]. Over half of the major aquifers of the world are in states of depletion[26], groundwater level declines have accelerated in about a third of the world's regional aquifers over the past four decades[25], groundwater storage loss over the continents contributes substantially to sea level rise[27,28], a large proportion of wells globally are at risk of running dry[29], and the majority of the world's rivers and terrestrial groundwater-dependent ecosystems are at risk to transgress environmental limits[30,31]. Global frames and analyses on groundwater challenges capture the stark reality found in the magnitude and extent of challenges relating to groundwater depletion and have widely succeeded in sounding alarm on the need for action on groundwater sustainability[32]. Yet, these same global crisis framings often flatten or simplify the nuanced place-based complexity facing water managers and groundwater users when presenting as a singular global narrative[33,34].

Indeed, it is challenging to find adequate representation of many of the defining characteristics in the regional depictions offered above in existing global groundwater studies[35]. We argue that it is necessary and overdue to square global and regional perspectives [cf.36] in addressing groundwater challenges. While global narratives are useful in catalyzing large-scale action and awareness building about the overall state of groundwater, context-rich regional perspectives are necessary to ensure groundwater sustainability science and transformations fit, match, and reflect place-based realities[37]. A growing collection of studies focus on system dynamics relating to groundwater under global change and globalization, such as timing the transgression of environmental flow limits[30] or quantifying virtual groundwater embedded in international trade[38]. Yet, no work to date has attempted to holistically synthesize the variety of global challenges studied in relation to groundwater sustainability or to analyze their spatial configurations and co-occurrences.

We propose *groundwater sustainability puzzles* (**Box 1**, **Figure 1**) as a concept and mapping approach to bridge the narratives and patterns that emerge from global groundwater analyses with local groundwater realities, and to advance the science of global-scale groundwater sustainability. Generically, puzzles are challenges where full or complete knowledge of a problem may not be immediately evident, require creativity to solve, involve the recognition of patterns and relationships among diverse elements, and can involve assembling pieces of information into a coherent whole. In abstract, puzzles aptly describe global groundwater sustainability challenges. Groundwater sustainability is a so-called 'wicked problem'[39,40], which are problems that are not easily defined or solved due to their embeddedness in complex social-ecological networks, often have contested desired system states due to a diversity of invested actors, and thus have no clear stopping criterion. More broadly, groundwater sustainability can be considered as an example of 'post-normal' science[41] given the uncertainty of the system(s) under study, the variety of potential value systems involved in the study and management of the resource, the high-stakes nature of actions, and the urgency of decision making. Both the 'wickedness' and 'post-normality' of groundwater sustainability further reflect the puzzling nature of groundwater sustainability.

These groundwater sustainability puzzles offer an approach that: (i) integrates the diverse ways in which groundwater dynamically interacts with and shapes biophysical, economic, and sociocultural systems[22,42]; (ii) better represents the strong regional patterns exhibited in these relationships; and (iii) bridges the contextual richness of local, place-based groundwater challenges with global narratives and analysis. We formulate the concept of groundwater sustainability puzzles as a collection of three spatially resolved landscape units represented as metaphorical puzzle pieces: (1) a first puzzle piece (*'groundwaterscapes'*) that represents the set of system functions that groundwater provides or supports across a holistic range of social, economic, ecological, and Earth systems for a given location, (2) a second puzzle piece (*'problemscapes'*) that represent the set of socioeconomic and biophysical risks, socioeconomic stressors, governance challenges, and equity considerations, and (3) a third puzzle piece ('*sustainability pathways*') that represents a broad suite of processes including social transformations, governance and management, and other mechanisms through which people continuously and adaptively act to navigate, manage, and/or shape their groundwater systems, their relationships with these systems, and their futures (**Figure 1a**).

In this work, in addition to presenting the *groundwater sustainability puzzle* concept, we focus on globally mapping and overlaying the first two puzzle pieces (**Figure 1b**) and conclude by discussing their possible interpretations and implications for the '*sustainability pathways*' puzzle piece. We do so as the first two puzzle pieces benefit from a sufficiently rich set of globally available, spatially resolved datasets documenting the social-ecological and Earth system functions and problems of groundwater systems to conduct a preliminary, first-order global mapping[43]. Conversely, adequate data availability does not presently exist to represent the processes involved in sustainability transformation pathways that are inherently more normative, socially grounded and moderated, and therefore difficult to systematically monitor, characterize, and map with global data. We return in the **Discussion** to reflect more extensively on possible future priorities and development opportunities with the groundwater sustainability puzzles.

By mapping, overlaying, and analysing these groundwater function and problem puzzle pieces, this study presents the most comprehensive and integrated assessment of global groundwater sustainability challenges to date. In total, the groundwater sustainability puzzles synthesize 17 best-available datasets documenting a wide array of groundwater system functions and problems, commonly grounded in a conceptual understanding of groundwater as a social-ecological system[40], and combined into landscape unit typologies using a leading, data-driven, and unsupervised classification method (**Figure 1c**, see **Methods** and the **Supplementary Information**). This analysis builds on the recent global mapping of groundwaterscapes[42] by developing a complementary global mapping of groundwater sustainability problemscapes. We then analyze spatial patterns in their co-occurrences and identify the resulting groundwater sustainability puzzles. Finally, we discuss potential use cases of the groundwater sustainability puzzle concept, and of the spatial patterns and datasets generated in this first-order global analysis.

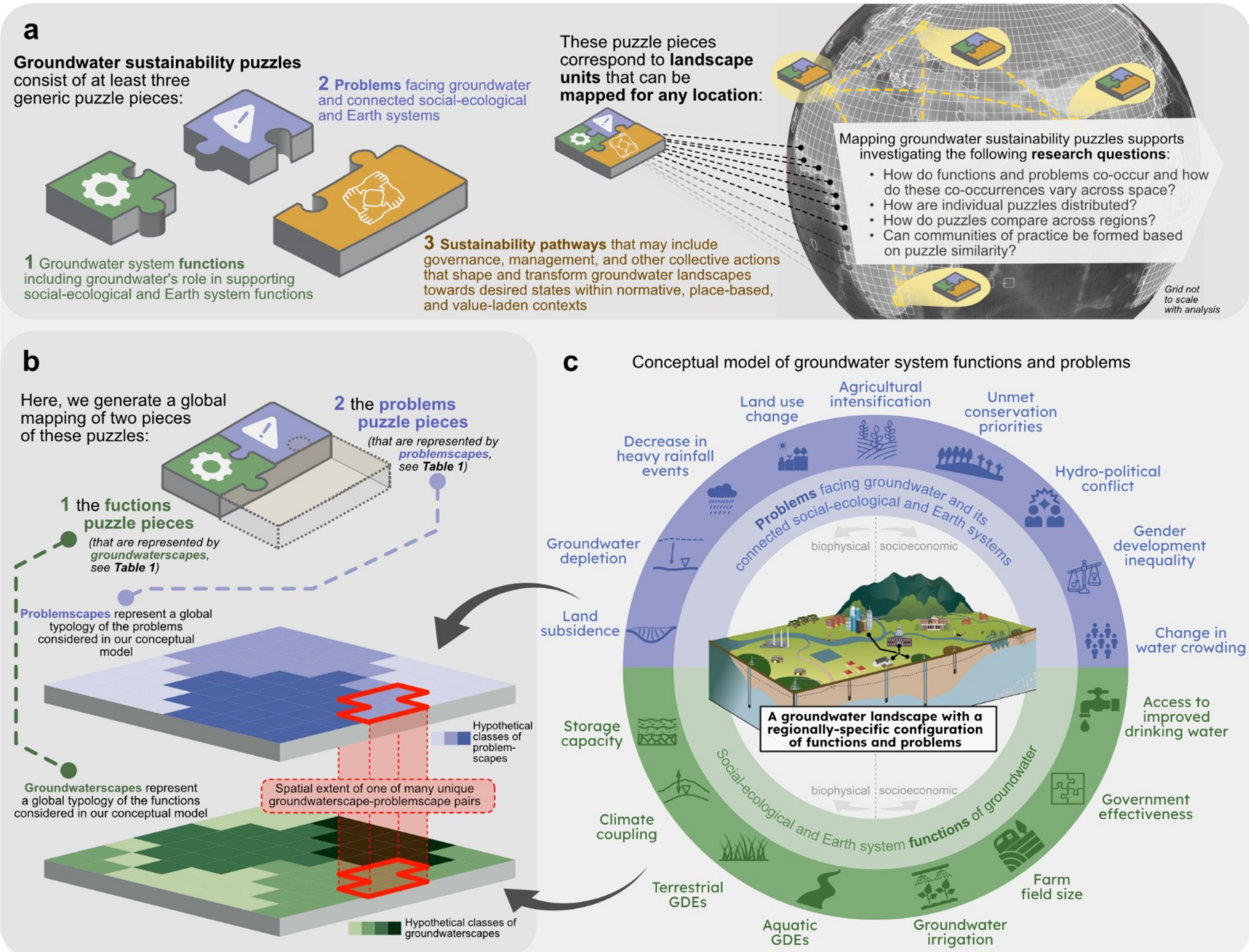


Figure 1: Groundwater sustainability puzzles. (a) An overview of the groundwater sustainability puzzle metaphor, the associated puzzle pieces, their geospatial aspects, and associated research questions enabled by the introduction of the sustainability puzzle concept. (b) The focus of this study is on mapping, spatially overlaying, and analysing two of the groundwater sustainability puzzle pieces: the first, which focuses on system functions; the second, which focuses on problems that are presenting to groundwater systems and its connected social-ecological and Earth systems. (c) The implemented conceptual model of the individual system functions and sustainability problems incorporated into the groundwater sustainability puzzle mapping in this study. All functions and problems shown in the conceptual model, informed by the understanding of groundwater as a resource embedded within social-ecological systems[40], is integrated into the groundwaterscapes and problemscapes derivation process, respectively, and are each underpinned by an existing, published global dataset (see **Extended Data Table 1** for data citations).

Box 1: Key terminology

Groundwater sustainability puzzles: Systematic characterizations of groundwater sustainability challenges through the combined consideration of system functions, problems, and sustainability pathways. Groundwater sustainability puzzles are spatial objects, in that they can be mapped for any location and are representative for an explicitly defined spatial extent, and are composed of three metaphorical puzzle pieces: (1) one piece to represent a location's specific configuration of groundwater *functions*, (2) a second piece to represent the location's specific configuration of *problems* facing groundwater and its connected social-ecological and Earth systems, and (3) a third puzzle piece that represents the location's specific set of potential *sustainability pathways*. Each puzzle piece represents a diversity of processes, these being the variety of system functions or problems within the extent of the puzzle piece (i.e., the spatial grain of analysis), and these diverse processes could be incorporated into the puzzle metaphor as the unique tabs and sockets of the puzzle pieces.

Groundwater sustainability puzzles are thus an approach to systematically characterize groundwater's social-ecological sustainability challenges for solution co-creation as "solving" these puzzles requires creativity and transformative thinking to align governance and management actions with diverse and entrenched values. Importantly, the puzzles should be understood as incomplete and evolving as many functions and problems are difficult to directly observe, quantify, or compare across regions, and are changing in time. Lastly, the concept of groundwater sustainability puzzles is flexible, and could be applied at various biophysical or institutional scales to support system diagnosis, comparison, and participation.

These puzzles draw on recent advances in groundwater systems theory[40], reviews of global groundwater functions and sustainability challenges[19,22–24], Anthropocene risk science[44], global change syndromes[45], and archetype analysis in sustainability science[46]. See **Methods** for further theoretical grounding of the groundwater sustainability puzzle concept in social-ecological systems, global change, sustainability, and resilience theory.

Here, we present a first, preliminary global derivation of the groundwater function and problem puzzle pieces, which are informed by best-available global datasets and that reflect large-scale processes and patterns on the order of 10^4 km^2 and larger.

Groundwaterscapes (GS): Landscape units representing configurations of groundwater's large-scale socioeconomic, ecological, and Earth system functions[42]. These functions include the support of groundwater-dependent ecosystems, groundwater storage capacity, agricultural reliance on groundwater, and dimensions of groundwater governance. The groundwaterscapes represent the spatially resolved form of the groundwater function puzzle pieces in our metaphorical model.

Groundwater *problemscapes (PS)*: Landscape units representing configurations of problems facing groundwater systems and their connected social-ecological and Earth systems. The individual problems included in our derivation of problemscapes include conventionally considered risks such as groundwater depletion and land subsidence, as well as often omitted, underrepresented, or emerging challenges such as hydro-political tension, gender inequality, and ecological conservation needs. A problemscape thus represents the spatial configuration of interrelated risks, stressors, and social challenges that collectively constitute groundwater sustainability problems. Problemscapes capture both biophysical risks and socially constructed dimensions of vulnerability, governance, and inequality that mediate system outcomes. Our derivation builds on the concept of Anthropocene risk[44], which relates to traditional risk components of hazard, exposure, and vulnerability, but extends to focus on anthropogenic changes to Earth system functions, processes unique to social-ecological systems such as inequality and injustice emergence, and cross-scale interactions that occur over potentially long time horizons and can involve Earth system tipping elements (see **Methods**). The resulting global problemscapes represent the spatially resolved form of the groundwater problem puzzle pieces in our metaphorical model. The geospatial classification methods to derive problemscapes apply the same approach used in the derivation of the groundwaterscapes[42].

Results

The mapped groundwater sustainability puzzles characterize the heterogeneous and high-dimensional composition of global groundwater sustainability challenges for the first time. This puzzle mapping makes clear that the world faces, and must navigate, many unique, context-specific, and interrelated groundwater sustainability challenges rather than a single crisis (**Figure 2**). In total, we have identified the spatial extent and characteristic composition of functions and problems for 270 unique sustainability puzzles by overlaying groundwaterscapes (**Figure 2a**) with problemscapes (**Figure 2b**). The potential may exist to similarly map the 'sustainability pathways' puzzle piece given future data availability, which would further disaggregate and refine this global typology, but we only consider 'sustainability pathways' here in our discussion. We focus on analyzing the groundwater sustainability puzzles rather than the underlying groundwaterscape and problemscape maps as the groundwaterscapes are already presented in ref.[42] while the problemscapes are summarized in **Box 2** and detailed in full in the Supplementary Information.

Box 2: Overview of the problemscapes

Eighteen groundwater problemscapes (PS) emerged from the data-driven classification of the underlying global groundwater problems data (**Extended Data Figure 1**). The problemscapes are distributed heterogeneously in large contiguous patches (**Extended Data Figure 1a**). For example, PS17 and PS18 (in the problemscape grouping VI, see **Extended Data Figure 1b**, characterized by extensive challenges including groundwater depletion, increased water crowding, gender inequality, and hydro-political tension) are prevalent throughout the Indian Subcontinent, PS2 (elevated hydro-political tensions and land subsidence) across much of the American Midwest, PS14 (gender inequality and increasing water crowding) across the Sahel, and PS7 (land subsidence) within northern Europe. PS6 (unmet conservation needs) has the least pronounced configuration of problem magnitudes but is the most extensive, covering 45% of global land area. This extent is consistent with findings that roughly half of Earth's land surface remains under very low human activity[47]. The next most extensive problemscapes are PS5 (extensive land use change and unmet conservation needs), covering about 7% of the land surface, and PS14 covering over 6%. PS15 (gender inequality, water crowding, and hydro-political conflict) is the smallest problemscape, at 1% surface coverage. Contrary to conventional problem and risk assessments, the problemscapes are not intended to be interpreted along a spectrum of severity, and we make no assessment on the need to prioritize action within one problemscape over another. Rather, the problemscapes present a descriptive set of region-specific problem configurations that shape the challenges and opportunities for groundwater sustainability transformations.

Each puzzle corresponds to a unique groundwaterscape-problemscape pair with a spatial extent dictated by the location of grid cells sharing the same pairing. Thus, we refer to puzzles using a nomenclature that combines the grid cell's groundwaterscape (GS) and problemscape (PS) identifications. For example, puzzle GS4-PS14 is the intersecting extent of groundwaterscape 4 and problemscape 14, and covers broad and spatially contiguous patches across the tropics of northern and central Africa, particularly within the central Sahel, Sudanian savanna, and in bushlands across the Horn of Africa (**Figure 3d**). This puzzle corresponds to regions where domestic water security remains underserved by groundwater, national governance remains limited or ineffective, a moderate density of terrestrial groundwater-dependent ecosystems, and where groundwater and groundwater-connected systems face a set of problems that includes high levels of gender inequality and increasing water crowding. These descriptive features are not identified arbitrarily but rather are the defining characteristics of these landscapes based on the reproducible, self-organizing map (SOM)-based derivation method implemented to define each groundwater sustainability puzzle (see **Methods**). The puzzle derivations and descriptions are not only based on the presence or absence of a certain subset of functions and problems but rather on the complete set processes and indicators included in our conceptual model (**Figure 1c**) and their respective magnitudes.

The structure of our puzzle piece mapping approach enables a multi-tiered understanding of similarity across regions by overlaying unique combinations of the groundwaterscape and problemscape typologies. For any grid cell, the spatial extent of corresponding regions can be categorized through the following cases. *Case 1*: regions that share the same groundwaterscape but face different problem; *case 2*: regions that share the same problemscape but have different functions; and *case 3*: regions that share both the same groundwaterscape and problemscape, representing the grid cell's associated groundwater sustainability puzzle (**Figure 2d**). This approach is thus highly amenable to apply and describe using set notation (see **Methods**). For any given grid cell i, the extent of the three cases above are defined by the relative complement $G_i \setminus P_i$ (case 1), the reverse complement $P_i \setminus G_i$ (case 2), and the intersection $G_i \cap P_i$ (case 3), where G_i and P_i are the sets of grid cells belonging to the same groundwaterscape and problemscape classes as grid cell i. This ability to construct and decompose groundwater sustainability puzzles based on their groundwaterscape and problemscape membership allows for a greater degree of region-to-region comparison, synthesis, and potential for network formation than what flat classification schemes can provide.

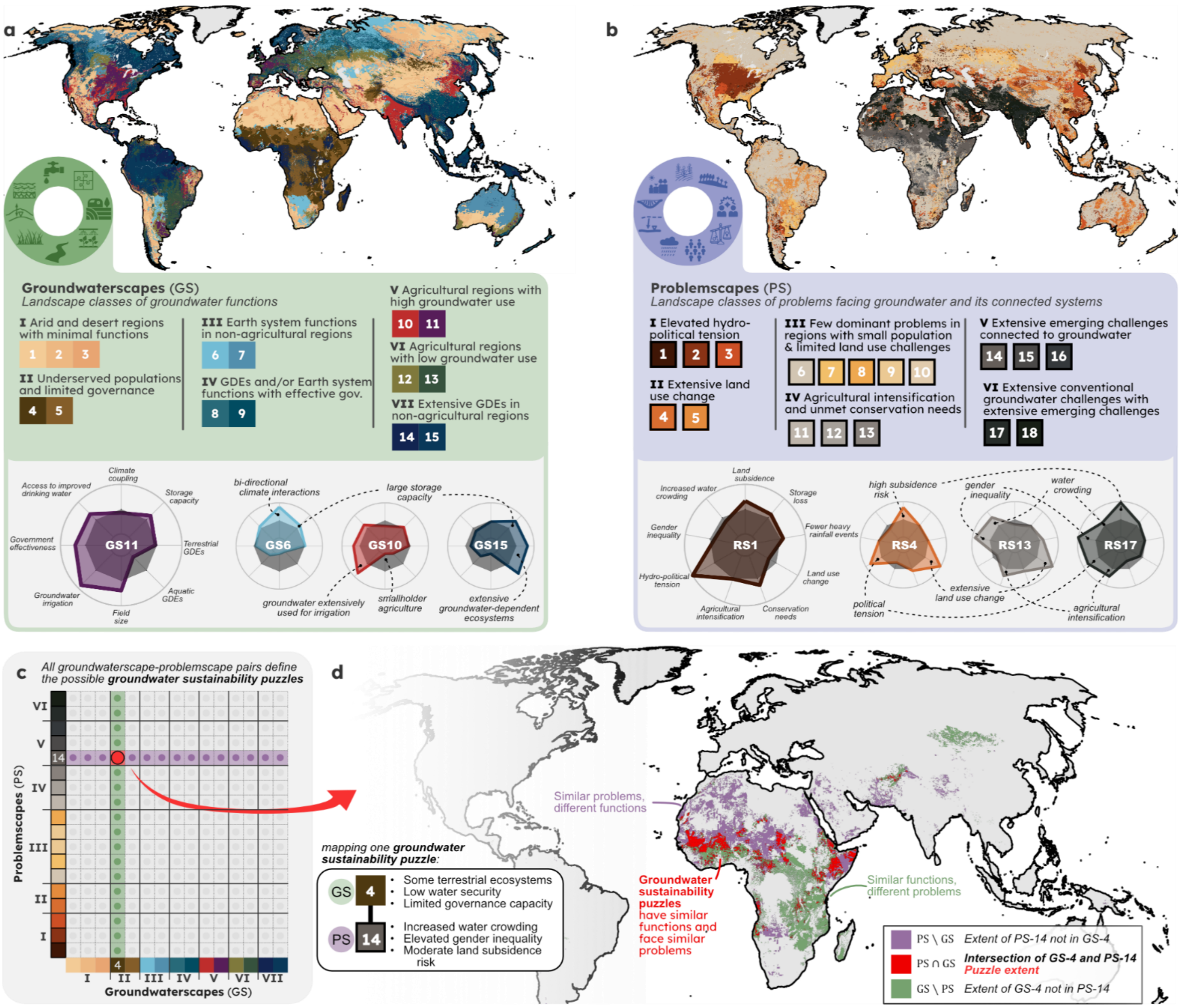


Figure 2: Composition of global groundwater sustainability puzzles. (a) Groundwaterscapes, landscape units of similar groundwater system functions. Groundwaterscapes represent the "function" puzzle piece of our metaphorical model. (b) Problemscapes, landscape units of similar problems facing groundwater systems and connected social-ecological and Earth systems. Problemscapes represent the "problem" puzzle piece of our metaphorical model. (c) The intersection of groundwaterscapes (n=15) and problemscapes (n=18) generates a set of 270 potential sustainability puzzles. (d) The extent of a single groundwater sustainability puzzle, demonstrated with the case of puzzle GS4-PS14 (i.e. the intersection of groundwaterscape 4 and problemscape 14). Note that we use set notation in our legend, where '\' represents the relative complement and '∩' represents the intersection operator.

Overall, the groundwaterscape and problemscape typologies are only weakly associated (normalized mutual information, NMI = 0.14), indicating there is little redundant information being captured across the two data-rich classification maps. Yet, there are some tendencies for certain problemscapes to co-occur more frequently with certain groundwaterscapes (**Figure 3a**). For instance, 40% of GS11 (industrial agriculture reliant on groundwater in nations with effective governance) overlaps with PS2 (political tension and land subsidence). Outside of co-occurrences between groundwaterscapes and PS6, which generally represents remote environments with little human pressures and is by far the most extensive problemscape, the intersection between GS11 and PS2 is the largest pairing across all remaining sustainability puzzles. Similarly, nearly 30% of GS5 (large storage capacity, moderate terrestrial ecosystem function, underserved populations and ineffective national governance) co-occurs with PS14 (gender inequality and water crowding). Excluding areas with minimal human activity (i.e., the extent of PS6), several groundwaterscapes have no dominant problemscape (GS2, GS3, GS8, GS10, GS12, GS14), for which no single problemscape co-occurs with over 25% of their remaining spatial extent.

The area distribution of puzzle sizes generally follows a log-normal distribution, and only 21 puzzles cover 1% or more of the global land surface (**Figure 3b**). The median groundwater sustainability puzzle has an extent of about 145,000 km^2 (an area approximately the size of Nepal). Furthermore, we find that puzzles with larger land areas tend to be more spatially contiguous, forming larger, fewer, and more cohesive patches (**Figure 3b**). The puzzle with the greatest spatial contiguity is GS11-PS2 (industrial groundwater reliant agriculture facing problems including hydro-political tension and land subsidence), and which is predominantly concentrated in a single, large patch across the Midwestern United States.

Every country matching or exceeding the scale of our analysis (i.e., with a surface area >10^4 km^2, which excludes small nations such as Singapore and Hong Kong) contains multiple groundwater sustainability puzzles. The median country contains 14 puzzles that cover at least 1% of national surface area, with Thailand navigating the greatest heterogeneity with 29 puzzles. The most dominant sustainability puzzle within each country covers about 25% of its surface area (IQR: 17% - 35%). Together, these emphasize the foundational challenge that political boundaries rarely align with the hydrological and social-ecological systems they are responsible for governing. Recognizing this heterogeneity may help underscore and advance efforts promoting flexible, adaptive, and multi-scalar policy instruments that offer better institutional 'fitness' when governing these water systems[37].

While the identification of over 200 groundwater sustainability puzzles may initially appear too numerous and granular to guide actions, only a small subset of these puzzles are spatially extensive or encompass extensive human activity. Indeed, the distribution of puzzles is strongly heavily tailed across land area, human population, and global crop production (**Figure 3c-e**). Only 15 puzzles collectively cover half of the global land surface (**Figure 3c**), while 20 puzzles encompass half of the global population (**Figure 3d**), and only 14 puzzles contain half of global crop calorie production (**Figure 3e**). Thus, while the complete set of groundwater sustainability puzzles already act in a simplifying manner to reduce an indeterminate number of unspecified groundwater sustainability challenges into a finite number of puzzles, the scope of this problem space may in fact be substantially less numerous and more tractable if prioritization is allocated to the few puzzles that characterize a disproportionately large fraction of the global land surface, population, and agricultural activity.

There is a strong level of consistency across the rank orders of these various distributions (Kendall coefficient of concordance, W = 0.86), meaning that the groundwater puzzles that are larger also tend to encompass more people and crop calories. The concordance between only the population and crop calories puzzle rank-orders is even more pronounced (W = 0.96), indicating highly similar distributions. These results suggest that focussing on a subset of heavily populated and agriculturally productive sustainability puzzles could have an outsized impact on people and food production systems in contrast to targeting all puzzles in parallel. For example, a prominent puzzle to focus on may be GS10-PS18 (**Extended Data Figure 2**), within which nearly one-tenth of the global population lives and over 6% of global crop calories are produced. This puzzle corresponds with smallholder farming regions highly reliant on groundwater irrigation with extensive sustainability challenges including land subsidence, groundwater storage loss, political tensions, gender inequality, and water crowding.

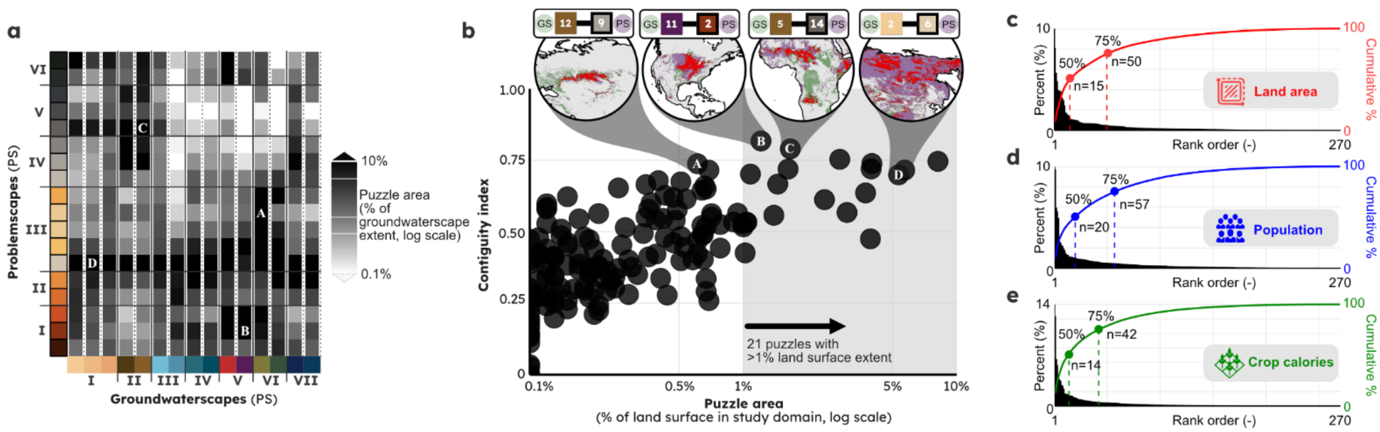


Figure 3: Extent, contiguity, and coverage of groundwater sustainability puzzles. (a) Areal coverage of individual puzzles, normalized per groundwaterscape size. (b) Comparison of contiguity index and land area of puzzles. The annotated points in the plot ('A', 'B', 'C', and 'D' correspond to annotations in panel a). Rank order and cumulative distributions of (c) land area, (d) human population, and (e) crop production across groundwater sustainability puzzles. Vertical annotations indicate the number of groundwater sustainability puzzles that collectively encompass 50% and 75% of the plot's respective distribution.

Discussion

Regional narratives to connect local and global perspectives, action, and science

A significant challenge for those managing and governing water is to better understand how global level changes and assessments can be used to inform local and regional decision-making. We observe a broad mismatch between how groundwater data are often collected, analysed and used and the ideals of context-appropriate groundwater governance and management, our third puzzle piece. For instance, while global groundwater storage analyses importantly highlight aquifers in California's Central Valley (USA) and across Iran as facing similar challenges in dropping water levels[25], the social-ecological approach and analysis conducted herein reveals how the problems facing groundwater, its connected systems, and their functions vary substantially between these regions (e.g., smallholder vs. industrial agriculture, presence vs.

absence of groundwater-dependent ecosystems, and different magnitudes of agricultural intensification potential, gender inequality, and ecological conservation needs). These limitations in existing studies do not derive from a lack of robust and useful hydrological assessment, which they importantly provide, but rather due to a limited engagement and analysis on the linked and entangled social-ecological dimensions and implications of this hydrological change[2,37,48]. It is our view that doing so may help relate groundwater to existing policy priorities, from climate action to biodiversity conservation to social development, and which in turn may foster more robust, integrated, and comprehensive groundwater management.

We hope the concept of groundwater sustainability puzzles will support and encourage a broad turn towards regional science and strategies in support of global groundwater sustainability. While the regional scale has long been identified as an important scale to target groundwater sustainability challenges[6], and important works have recently shed light on the regional patterns in specific groundwater sustainability challenges such as groundwater depletion[25], little work to date has sought to synthesize the heterogeneity of groundwater functions and problems across social-ecological systems at this scale. In our puzzle derivation approach, we focus on processes and outcomes that can be characterized on the order of 10^4 km^2 and larger but omit granular, local scale processes such as microclimate regulation within individual stream reaches or the provision of place-based cultural services, and focus on regional expressions of global change, such as the increase in heavy rainfall events driven by a warming climate. These decisions aid the puzzles to fit in-between, and to act as a much-needed link, across local and global scales of groundwater science. Thus, this work responds to a growing chorus of scholars highlighting that working across scales is necessary for ethical and grounded groundwater stewardship[2,48–50]. We address this call by developing and applying a method that bridges scales while retaining consideration of multiple processes relevant to groundwater governance and management.

The puzzles mapped in this study offer a first attempt at characterizing the regional diversity of groundwater sustainability challenges and support the systematic identification of region-specific descriptions of these challenges (**Figure 4**). Through the puzzles, regional, data-driven depictions can be generated for any region, such as within Burkina Faso (**Figure 4a**, as already described in relation to **Figure 2d**); or equally for agricultural economies in Mato Grosso (Brazil) that are situated among groundwater-dependent ecosystems undergoing land use change, land subsidence, and realising impacts of unmet area-based conservation needs (**Figure 4b**); political tensions and land subsidence in California (USA) within industrial, groundwater-irrigating agricultural regions (**Figure 4c**); and the intersection of smallholder farming highly reliant on groundwater irrigation in Andhra Pradesh (India) tasked with navigating groundwater depletion, land subsidence, agricultural intensification, gender inequality, water crowding, and hydro-political tensions (**Figure 4d**).

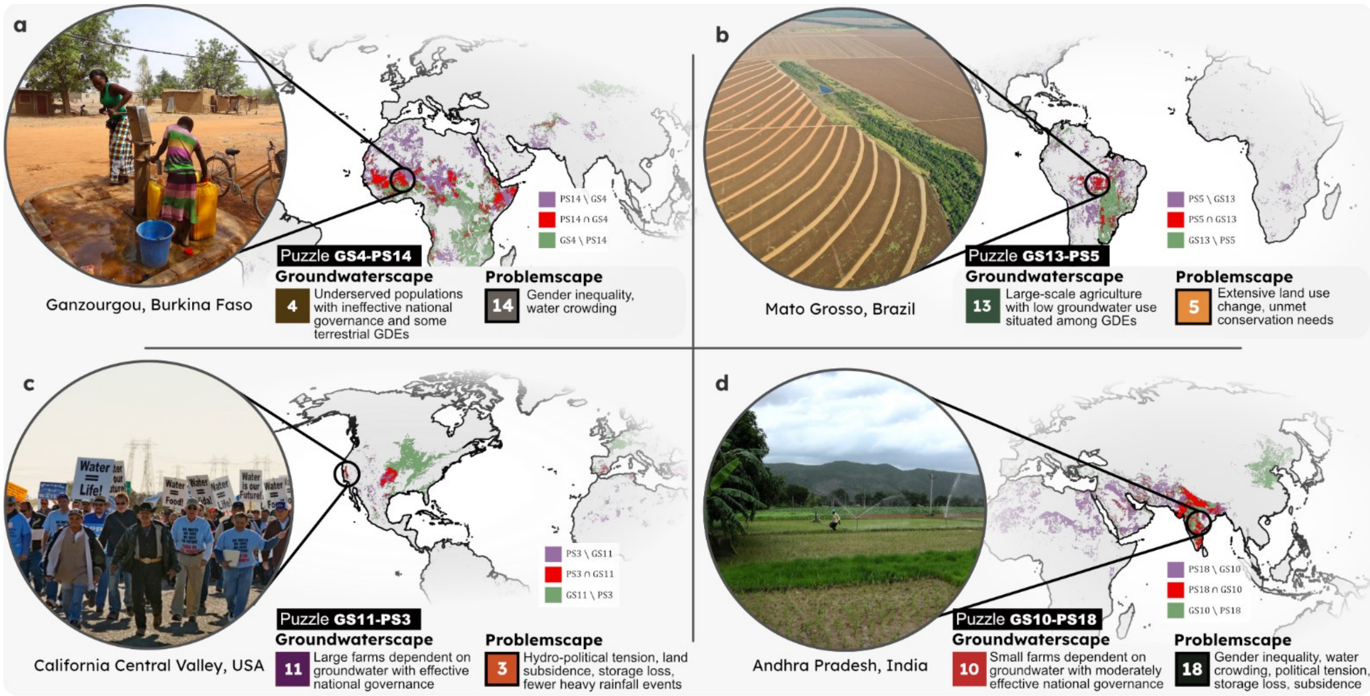


Figure 4: Regional characterizations systematically identified through mapping groundwater sustainability puzzles. (a) Ganzourgou, Burkina Faso. (b) Mato Grosso, Brazil. (c) California Central Valley, USA. (d) Andhra Pradesh, India. See Acknowledgements for image sources.

Wide conceptual and implementation applicability of sustainability puzzles

We envision different ways that groundwater sustainability puzzle mapping could be useful across a wide range of applications and users (**Figure 5**). First, we consider the utility of groundwater sustainability puzzles to act as templates for inter-regional network formation and solution transfer. Secondly, we view the holistic definition of groundwater sustainability puzzles as an opportunity to engage diverse actors in the form of a boundary object. Finally, we reflect on the possibility that top-down, data-driven system typologies such as ours may be perceived as overly simplistic, reductive, or problematically definitional, and on the opportunity for bottom-up approaches to contest, reject, or replace such global analyses.

Figure 5: Potential use cases for the groundwater sustainability puzzles.

A primary potential use case is for the puzzles to act as a tool to consider the suitability of cross-regional learning, shared strategies, and network formation across regions (**Figure 5**, panel 1). For instance, none of the regions highlighted in Figure 4 share a groundwaterscape nor a problemscape and these differences may suggest that sustainability strategies pursued in any of these regions could have different outcomes or unforeseen consequences in other regions if contextual differences are not accounted for. Alternatively, the extent of individual groundwater sustainability puzzles can be used as a spatial template to consider candidate regions for strategy sharing and cross-regional learning. While some puzzles are regionally constrained (e.g., GS10-PS18, which is found extensively and nearly exclusively throughout the Indian subcontinent) other puzzles are more globally distributed. For instance, puzzle GS11-PS03 (**Extended Data Figure 3**), which characterizes California's Central Valley (USA), is also found in a subset of regions in the Pampas (Argentina), the southern Iberian Peninsula (Spain and Portugal), and the Songliao Plain (China).

The classification of certain distal regions within the same puzzle may appear unexpected and yield counterintuitive groupings, as prevailing approaches to characterize global groundwater systems typically consider fewer dimensions than our broad, multidimensional, social-ecological systems approach. In this way, the groundwater sustainability puzzles can usefully contest and disrupt dominant modes of understanding global groundwater systems and their sustainability challenges and forge new insights and connections between regions that have often, until now, been assumed to be disconnected or dissimilar. Furthermore, groundwater sustainability puzzles may help establish communities of practice among water managers, researchers, and water professionals to share best-practices, lessons, successes, and overarching strategies across spatially distant regions confronting similar challenges[37]. More broadly, the puzzles can support context-specific governance and management while countering misconceptions of groundwater sustainability panaceas[51–53].

One practical use of groundwater sustainability puzzles lies in their ability to engage diverse actors in holistic and interdisciplinary problem identification (**Figure 5**, panel 2). Given the inclusion of processes beyond physical groundwater hydrology, including ecology, agriculture, Earth systems, and governance, myriad disciplines and forms of expertise are needed to develop, understand, and apply sustainability puzzles. In this way, groundwater sustainability puzzles can act as a boundary object to engage a broad community of academics, practitioners, policy makers, partners and stakeholders, each with vested interests in shaping groundwater sustainability definitions and pathways. This may already be possible with the global puzzles presented herein, yet could become even more powerful and meaningful if the puzzle concept were applied at other scales.

Finally, we acknowledge and welcome the valid and likely sceptical interpretations of the groundwater sustainability puzzles and the top-down, data-driven methods used herein to characterize them. There are many frames and methodologies arguing that bottom-up approaches, grounded in lived experience, social relations, and place-based knowledge, are more effective for enabling groundwater sustainability transformations. This perspective is evident in the growing literature and in the welcome proliferation of groundwater transformation "labs" (e.g., WELL Labs[54], Transformations to Groundwater Sustainability[55], CLARITY Lab[56]). These initiatives directly engage with fundamental yet unresolved questions in the global groundwater crisis literature—namely, what must change, who must act, and what are the desired system states—through co-creation, deliberation, and action.

The data-centric approach applied in this study does not directly address these relational and normative dimensions. Yet rather than viewing these approaches as contradictory, we see them as complementary and mutually beneficial. The groundwater sustainability puzzles provide a global, conceptual scaffolding that can inform, be adapted by, and evolve through participatory and context-specific initiatives. In this way, future work could reinterpret or co-develop the puzzles within local contexts, integrating new qualitative or governance dimensions in an iterative and participatory manner to bridge bottom-up and top-down approaches in pursuit of shared sustainability goals.

Puzzle limitations

Groundwater sustainability puzzles are inherently imperfect and incomplete as data availability, cognitive bias, and incompatibility of data forms limit the ability to express an exhaustive description of all conceivable system functions and problems. This limitation mirrors the challenge being navigated in emerging 'digital twin' Earth system models, where retaining the full realism of a system offers little explanatory power and likely remains fundamentally unattainable[57]. In this sense, the foundational challenge of the groundwater sustainability puzzles may not relate to their simplifying effect on regional system characterisations, but rather on the uncertainties, contested perceptions, and technical limitations in constructing more useful regional portraits of groundwater sustainability challenges.

Yet, despite these limitations, the concept of groundwater sustainability puzzles provides a structural approach to understand groundwater sustainability challenges as a mosaic of interlinked puzzles distributed across the world rather than as a singular global crisis. In this way, groundwater sustainability puzzles might not offer a grand solution, but rather they represent an important stepping stone that succeeds in pluralising the global groundwater sustainability discourse, illuminating systemic challenge similarity across distal regions, supporting inter-regional network formation, and advancing the science on groundwater dynamics and sustainability problems in social-ecological systems.

While our analysis integrates an unprecedentedly wide range of groundwater problems and functions, our conceptual model does not explicitly consider coastal or cold region dynamics, and centers shallow groundwater systems (i.e., within the upper ~100 meters of Earth's crust) in continental landscapes such as plateaus, high plains, riverine valleys, hummocky terrains, and playa [cf.58]. There are also a variety of sustainability challenges not represented due to overly coarse data (e.g., virtual water trade) or lack of globally extensive data availability (e.g., wells running dry). This study also focuses on the functions and problems related to groundwater quantity but overlooks those principally related to groundwater quality. These omissions overview the multitude of ways the sustainability puzzle concept could be adapted for application to wider domains. Furthermore, this study does not intend to frame global groundwater sustainability challenges as purely technical or quantitative. Many important sustainability considerations are not well represented in global datasets due to methodological limitations or ethical considerations, such as groundwater's role in sustaining senses of place and ceremonial practices.

Our mapping of global groundwater sustainability puzzles is limited to a static analysis due to inconsistent or unavailable temporal data[43] across the input features considered in our conceptual model. The static nature of our study constrains our ability to evaluate causal relations among these processes, though such dynamics could be explored in future work given improved time-resolved data.

Despite these static data constraints, the underlying method used here to assess the co-occurrences of functions and problems could provide a foundational starting point for future work aimed at understanding the dynamic mechanisms linking these processes and outcomes. Addressing the substantial uncertainties associated with these interactions may be better approached through stylized, process-based, and qualitative dynamic models rather than through global empirical dataset development. Our classification approach, based on self-organizing maps (see Methods), is well suited for these applications as each class is defined by a codebook vector that retains the full dimensional structure of the input feature space and preserves the physical meaning of individual variables. This advantageously contrasts with dimensionality reduction methods such as principal component analysis or empirical orthogonal functions which project data onto orthogonal axes that can obscure relationships among input variables and complicate physical interpretation. Development of models that generate mechanistic insights into dynamic change in the coupled social-ecological systems characterized by groundwater sustainability puzzles could help develop important but missing theories of system change [cf. 59] in global groundwater science.

In sum, we have introduced a new conceptual approach in groundwater sustainability puzzles, and applied it to produce the most holistic and spatially explicit synthesis of the wicked and global challenge of groundwater sustainability to date. This approach is strongly aligned with contemporary definitions of groundwater sustainability, which maintain the importance of a physical water balance while extending to also prioritize maintaining the functions provided by groundwater systems, consideration of intergenerational and spatial equity, and governance mechanisms[22]. While the presented first-order global mapping detailed here represents a substantial advance in spatially differentiating the diversity of settings in which groundwater sustainability transformations must take root, the work remains conceptual and illustrates a widely implementable approach. Ultimately, we encourage readers to critically engage with the groundwater sustainability puzzles, consider the adaptations that can make the concept more suitable for alternative scales and context-specific framings, and embrace the interdisciplinary and complex systems science needed to meet groundwater sustainability needs.

[end of main text]

Methods

Spatial scale and data processing

All data used in this study are sourced from previously published datasets. All analysis was performed at 5 arcminute resolution (~10 km grids near the equator). **Extended Data Table 1** summarizes all input datasets, preprocessing steps, and resolution harmonization methods.

Conceptualization of problemscapes

We consider groundwater problems through a broad framing that enables representation of the diverse biophysical, social and institutional challenges that emerge from social-ecological processes and interactions connected to groundwater systems. To do so, we fundamentally draw from the concept of Anthropocene risk[44], which conceptualizes risk as not only a product of hazards, exposures, and vulnerabilities but as a property of cross-scale interactions in coupled human-Earth systems, and that centers the potential for inequality emergence in these processes. In our problemscapes, we extend this concept by recognizing that many groundwater sustainability challenges are not easily captured by conventional risk definitions and risk language and therefore adopt a wider scope that accommodates both quantifiable risks and the social, institutional, and justice dimensions of groundwater sustainability.

Our conceptual model identifies nine key groundwater sustainability problems (**Extended Data Table 1**) that reflect both human-mediated Earth system changes and unequal social impacts that may arise from them. These problems span multiple Earth system domains, including the hydrosphere, lithosphere, atmosphere, and biosphere (inclusive of human activities including governance). This broad approach enables the inclusion of traditionally considered biophysical hazards in addition to often underrepresented but emergent and increasingly recognized social-ecological challenges. Problems such as groundwater storage loss, land use change, agricultural intensification, and increased frequency of heavy rainfall represent human impacts on physical

Earth systems, while problems such as water crowding, unmet ecological conservation needs, hydro-political conflict, and gender development inequality highlight the uneven distribution of vulnerabilities within social-ecological systems linked to Earth system change. Each problem included in our conceptual model is underpinned by a global, previously published dataset. Justification for the inclusion of each problem in our conceptual model is provided in **Extended Data Figure 1**. The scope of our problemscape analysis is limited by data availability, and problems related to wells running dry, social displacement, cultural loss, and biodiversity impacts are all not included due to this constraint.

These nine problems are not isolated but frequently interact. For instance, agricultural intensification and land use change can reduce groundwater recharge and lead to groundwater depletion[60,61], land conversion can undermine ecological conservation priorities[62], water crowding can heighten hydro-political tensions or conflict[63], and groundwater depletion can exacerbate gender inequalities in regions where responsibilities for collecting drinking water disproportionately fall on women[9]. These processes also importantly interact with the functions included in the groundwaterscapes. For instance, land use change can threaten the integrity or presence of groundwater-dependent ecosystems[64], groundwater storage loss can alter the directional mode of climate-groundwater interactions[65], and land subsidence reduces aquifer storage capacity[66]. Conversely, the processes underpinning these functions can also shape the problemscapes. For instance, ineffective governance can create conditions that foster hydro-political tensions[20], and groundwater irrigation is a prevalent driver of groundwater storage loss[61]. These two-way interactions are central to our conceptualization of groundwater sustainability puzzles; however these interaction processes are not explicitly represented in our temporally static analysis.

Our set of considered problems consist of both snapshot data (i.e., corresponding to a single timestamp such as gender development inequality for the year 2020) and trend data (i.e., corresponding to a change over time, such as the change in water crowding between the year 2020 and 2050). Our use of either snapshot or trend data for each problem depends on whether the principal challenge is found in the magnitude of the problem itself (snapshot) or in a change in its magnitude (trend). For static (snapshot) data, we use data as closely aligned to the year 2020 as possible. For trend data, time ranges are best selected under data availability constraints. All data sources and preprocessing steps are provided in **Extended Data Table 1**.

Problemscape derivation using self-organizing maps

We implement the same sequential, self-organizing map methodology[67] developed and implemented to derive the groundwaterscapes these problemscapes complement[42]. This approach trains an ensemble of thousands of self-organizing maps (SOMs) across a wide range of nodal lattice architectures, in two distinct classification 'stages. First, a wide range of two-dimensional square SOM lattices, whose range is set based on the underlying complexity of the input data, are trained on the full input feature space to produce an intermediary classification scheme with associated codebook vectors providing a synthetic representation of the input data with its full dimensional structure yet with a substantially reduced feature count. Secondly, a second range of one-dimensional SOM lattices are trained on the codebook vectors (i.e., the loading factors of individual SOM nodes) from the best-performing first-stage SOM. Following removal of performance outliers to improve classification reproducibility, the best-performing one-dimensional SOM determines the number and the composition of the problemscapes. This multi-tiered classification approach allows for a simple mapping of problemscape results back to geographic space based on the nested membership of grid cells to first-stage SOM nodes, and of first-stage SOM nodes to second-stage SOM nodes. A visualization of the derivation methodology is shown in **Extended Data Figure 4**, including the preprocessing step of normalizing each input risk raster layer (**Extended Data Figure 5**). As data layers had variable spatial coverage, we trained our SOM classification using only locations where the full set of data were available. For areas with partial input data coverage, problemscape classifications were inferred by pairing each of these grid cells to their most similar grid cell with complete data coverage. Similarity was determined using a nearest-neighbour distance function applied to the available input variables only (i.e., similarity was calculated in the input feature space, not by spatial distance), and thus grid cells with incomplete data coverage were assigned the problemscape class of their most similar first-stage SOM codebook vector. This treatment of areas with partial data coverage ensures globally consistent spatial extents between the groundwaterscapes and problemscapes. In regions where no data availability reflects the natural absence or bounded extent of relevant processes rather than dataset limitations (e.g., unpopulated or non-agricultural areas), we imputed a normalized no-change score (see panel annotations in **Extended Data Figure 5**). We applied this no-change imputation step after finding that classification assignments based on partial data coverage exaggerated the influence of certain problem signals that reduced the spatial coherence of the assigned problemscapes. A full description of SOM classification details is provided in the **Supplementary Information**.

Groundwater sustainability puzzle mapping and analysis

To formalize the spatial relationships between groundwaterscapes and problemscapes, and thus the global distribution of groundwater sustainability puzzles, we outline below a simple set theory notation for mapping grid cells across the two 'crisp' classification schemes:

Let Ω be the set of all grid cells in the study domain.

Let $GS\colon \Omega \rightarrow \{1, \ldots, 15\}$ denote the groundwaterscape classification raster, and

$PS\colon \Omega \rightarrow \{1, \ldots, 18\}$ denote the problemscape classification raster.

For any grid cell $i \in \Omega$, the local groundwaterscape class is defined as $g = GS(i)$, and the local problemscape class as $p = PS(i)$.

Any other grid cell in the study domain is represented by $j \in \Omega$.

The set of all grid cells sharing the same groundwaterscape as grid cell i is:

$$G_i = \{ j \in \Omega \mid GS(j) = g\},$$

and the set of all grid cells sharing the same problemscape as grid cell i is:

$$P_i = \{ j \in \Omega \mid PS(j) = p\}.$$

The spatial extent of regions that share the same groundwaterscape, problemscape, and their overlap (i.e., groundwater sustainability puzzle) as grid cell i can be expressed as:

Extent of grid cells sharing only the same groundwaterscape: $G_i \setminus P_i$

Extent of grid cells sharing only the same problemscape: $P_i \setminus G_i$

Extent of grid cells sharing the same groundwaterscape and problemscape (i.e., extent of the groundwater sustainability puzzle corresponding to grid cell i): $G_i \cap P_i$.

We calculated the normalized mutual information (NMI) between groundwaterscape and problemscape rasters to evaluate their similarity. NMI quantifies the amount of shared information between two categorical datasets, normalized by the sum of their individual entropies[68]. Thus, an NMI of 0 indicates that datasets are completely independent whereas an NMI of 1 indicates a perfect alignment of categories. NMI is computed as:

$$NMI(GS, PS) = \frac{2 \times MI(GS, PS)}{H(GS) + H(PS)}$$

where $MI(GS, PS)$ *represents the mutual information of the two categorical variables* GS *and* PS *(i.e., the groundwaterscape and problemscape classification rasters), and where* $H(GS)$ *and* $H(PS)$ *represent the individual entropies of these variables.*

To generate a single global raster of the puzzles, we developed a simple four-digit integer coding system with the first two digits representing the groundwaterscape class, and the last two digits representing the problemscape class assigned to each grid cell. The 15 groundwaterscape classes are encoded as values from 01XX to 15XX, and the 18 problemscape classes from XX01 to XX18. Thus, a grid cell with the code 0118 corresponds to sustainability puzzle GS01-PS18, while a code of 1201 corresponds to GS12-PS01. Each groundwater sustainability puzzle is treated as a unique class in our landscape metrics calculations.

We calculated the spatial contiguity index of groundwater sustainability puzzles to quantify their spatial connectedness. For each puzzle, we first identified all patches (contiguous groups of grid cells with the same puzzle class) and then calculated the contiguity index[69] for each individual patch, which quantifies the degree to which cells within a patch are spatially cohesive and internally connected. To evaluate spatial connectedness at the puzzle level, we computed the area-weighted mean contiguity index across all patches belonging to each puzzle. A puzzle with an area-weighted contiguity index of 1 is composed of a single, compact, and internally cohesive patch, while values approaching 0 indicate that a puzzle is fragmented into many spatially disconnected or elongated patches. All spatial metrics were computed using the *landscapemetrics* package[70] in R.

Code and data availability

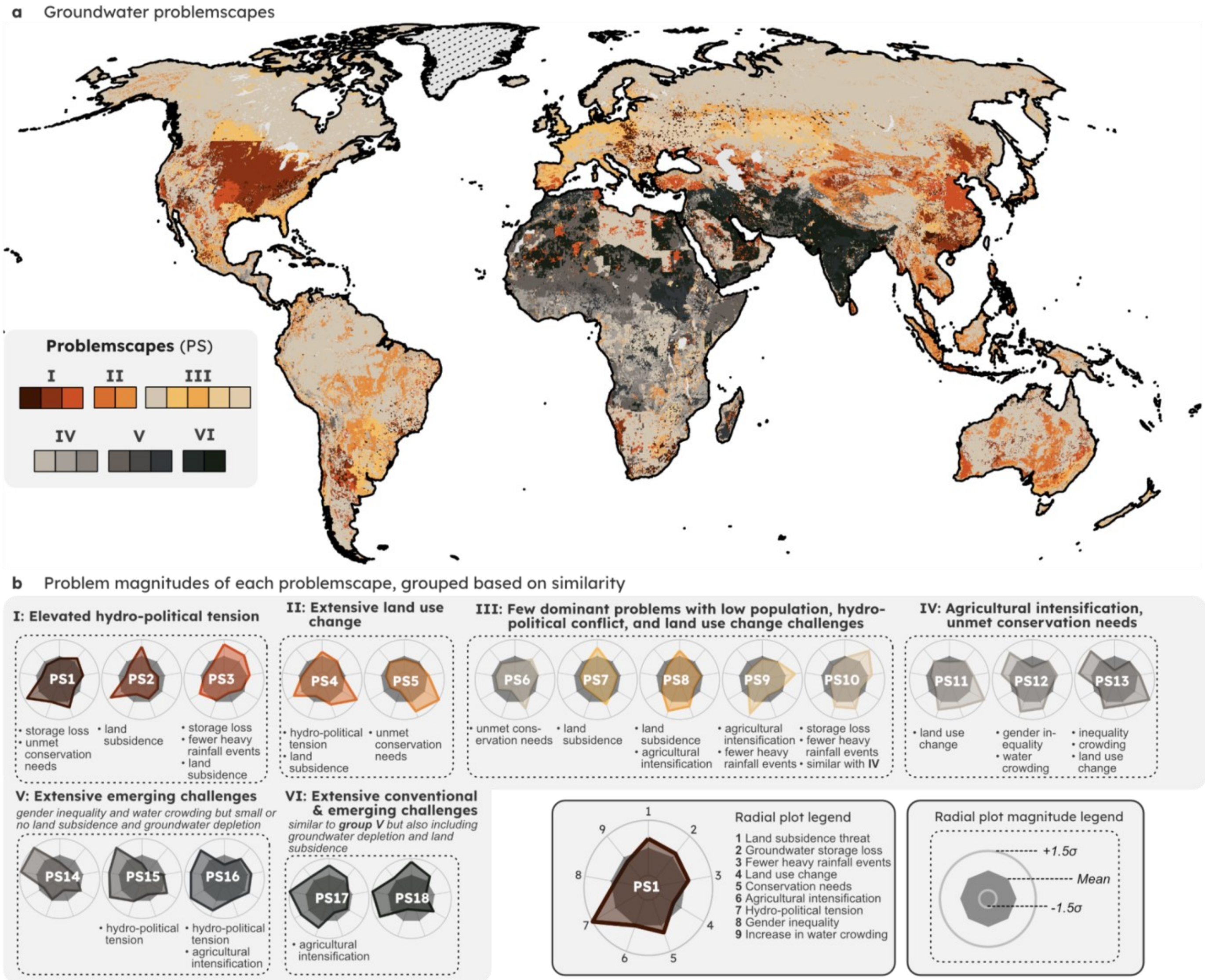
All analyses were conducted using the R project for statistical computing[71]. R packages necessary to perform this study include: *kohonen*[72], *aweSOM*[73], *clusterSim*[74], *landscapemetrics*[70], entropy[75], *terra*[76], *tmap*[77], *ggplot2*[78], and *MetBrewer*[79]. Composite figures were assembled in Affinity Designer (https://affinity.serif.com/en-us/designer). All scripts are available on the study's GitHub repository: https://github.com/XanderHuggins/global-puzzles/ . These scripts will be archived alongside the groundwater sustainability puzzle raster on Borealis (https://borealisdata.ca), the Canadian Dataverse Repository, following manuscript acceptance.

Acknowledgements

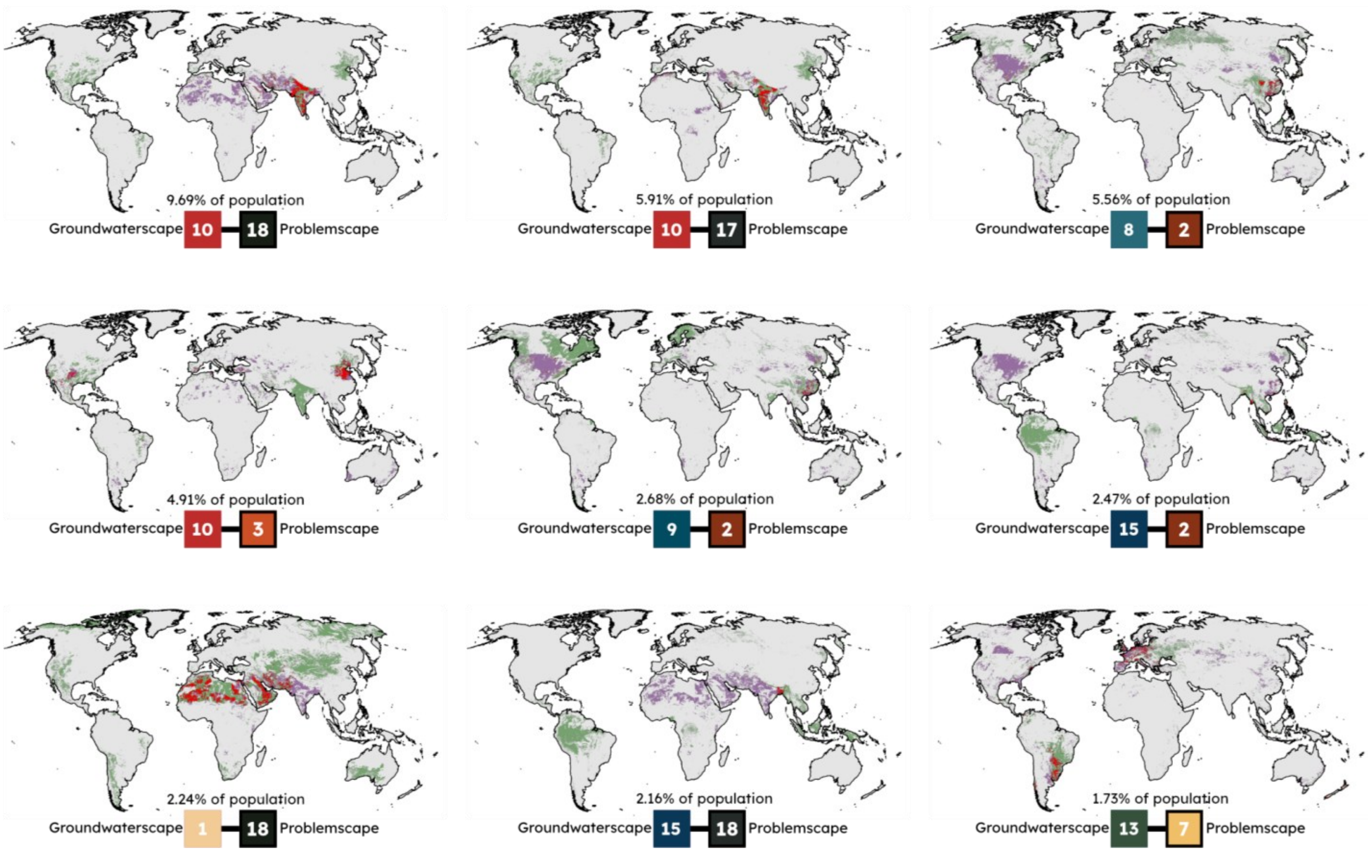
This work was supported by a fellowship from Natural Sciences and Engineering Research Council of Canada (NSERC), a financial contribution from the Canadian Space Agency, and by a gift from William H. Miller III.

Some vector graphics incorporated into the figures are sourced from the Noun Project (CC BY 3.0) and include: "Rain" by Kang Girih, "land use" and "Degradation" by Nithinan Tatah, "farm crops" by Made, "Conflict" by Chintuza, "gender inequality" by WiStudio, "crowd" and "groundwater" by Adrien Coquet, "foraging" by Kevin, "river" by Alvida, "farm field" by Singlar, "Game" by faisalovers, "Faucet" by Salman Azzumardi, "teamwork" by Larea, "Caution" by Jardson Almeida, "Gears" by Gregor Cresnar, "area" by Ian Banyuke, "population" by Purple Iconix, "field" by Studio 365, "Handshake" by Anggun, and "Handshake" by Fission Strategy. The central vector graphic in Figure 1 panel (c) is reproduced with permission from Huggins, X. © 2023 The Authors. Groundwater published by Wiley Periodicals LLC on behalf of National Ground Water Association (CC BY-NC-ND 4.0). Embedded photographs in Figure 4 are sourced from the Water Alternatives (CC BY-NC 2.0) and GRID-Arendal (CC BY-NC-SA 2.0) Flickr accounts and include photographs by Dominique Mercier (panel a), Riccardo Pravettoni (panel b), Dale Kolke (panel c), Jake Burke (panel d).

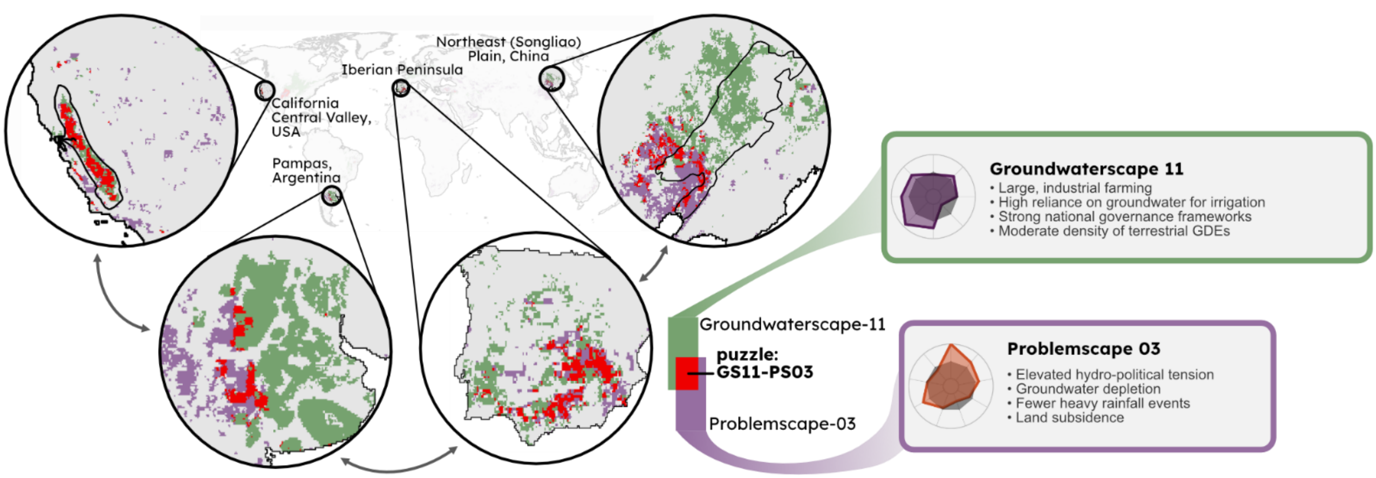
Extended data figures



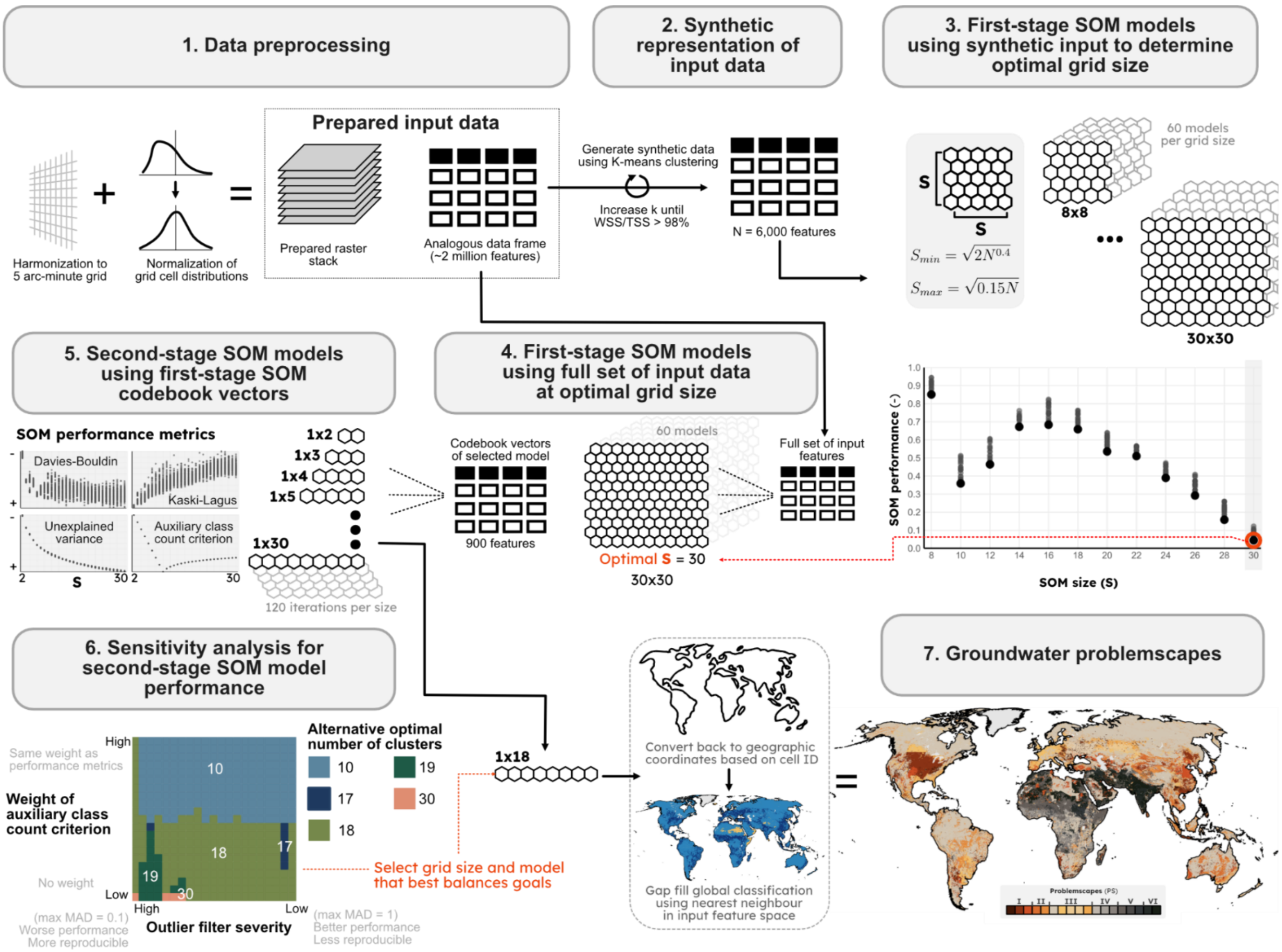
Extended Data Figure 1: (a) Groundwater problemscapes. (b) Radial plots representing characteristic configurations of problem magnitudes per problemscape. See radial plot legend (bottom right) for interpretation guides.



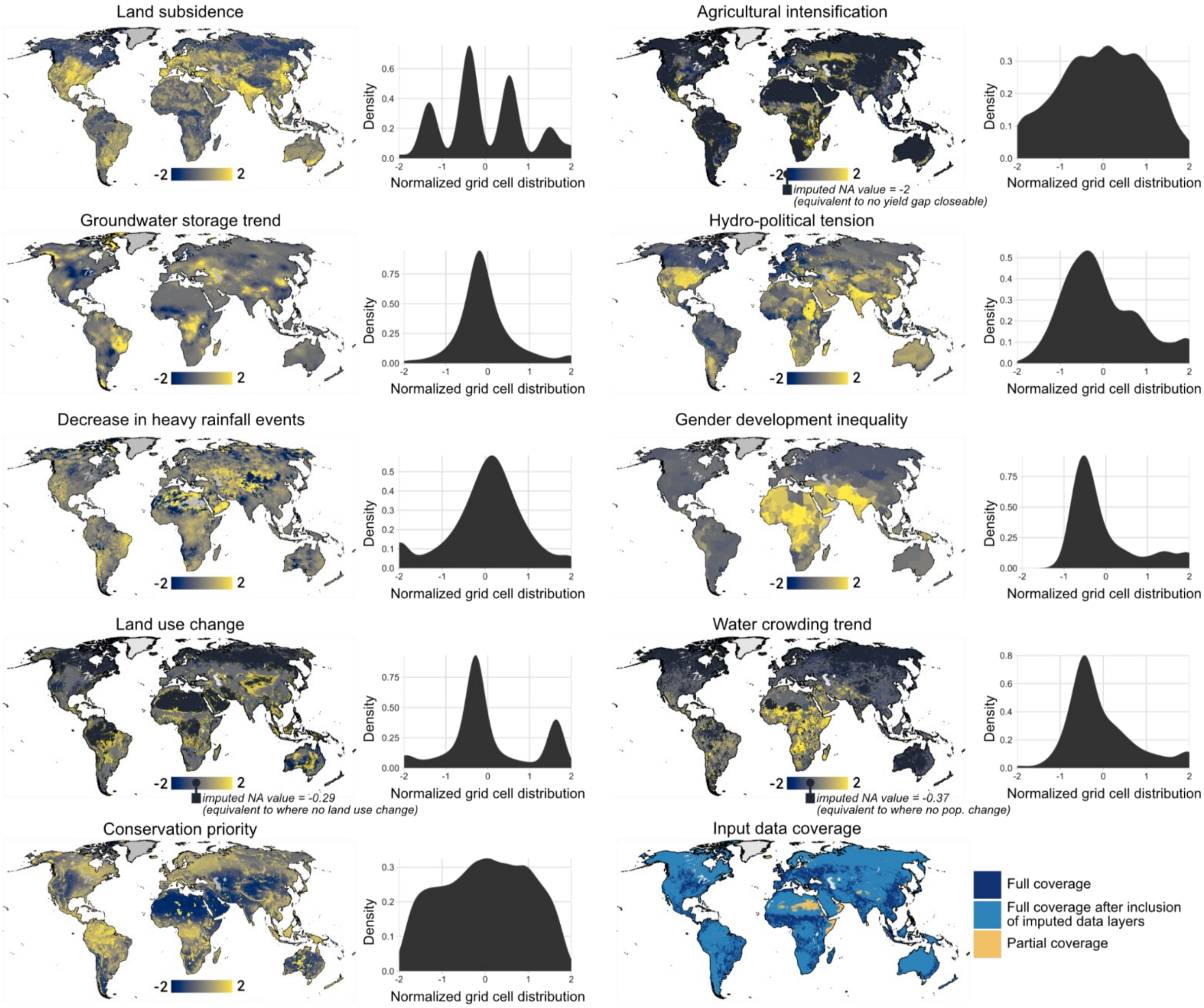
Extended Data Figure 2: The groundwater sustainability puzzles encompassing the greatest proportion of the world population.



Extended Data Figure 3: Regional inset maps revealing the distribution of groundwater sustainability puzzle GS11-PS3, highlighting the potential for puzzles to facilitate cross-regional learning, shared strategies, and network formation across distal environments facing similar sustainability challenges.



Extended Data Figure 4: Problemscape derivation method, which follows the groundwaterscape derivation method[42] with minor adjustments to account for gap filling requirements. Numbered panels and aSrrows denote order of steps.



Extended Data Figure 5: Individual input problem rasters after preprocessing and normalization. Grid cell distributions for each raster layer are shown to the right of each map. We show grid cell distributions rather than area distributions as each grid cell contributes equally to the training data of the problemscapes. For land use change, agricultural intensification, and trend in water crowding datasets, no-data values were imputed to reflect the natural absence or bounded extent of these challenges. Imputed regions did not contribute to the problemscape training data but rather were used in assigning problemscape classes to regions excluded from the training set.

Extended Data Table 1: Groundwater sustainability problems included in our conceptual model of problemscapes. Rationale for inclusion, data source, persistent web link, spatial scale, temporal resolution, resolution harmonization and other preprocessing steps are detailed for each problem.

Groundwater sustainability problem	Rationale, metadata, and preprocessing steps
Land subsidence	**Rationale**: Can cause irreversible loss of aquifer storage capacity. **Indicator**: Global potential subsidence. **Source**: Herrera-García et al. (2021)[80] **Persistent web link**: http://doi.org/10.6084/m9.figshare.13312070.v1 **Temporal range**: 2010 **Spatial resolution**: 30 arcseconds **Resolution harmonization method**: Maximum value aggregation **Additional preprocessing**: None
Groundwater storage trends	**Rationale**: Change in groundwater availability, which can be caused by human use (pumping), land use change, climate change, and natural variability; and experienced through lower water tables, detrimental groundwater-dependent ecosystem states, and altered groundwater-climate interactions. **Indicator**: Trends in groundwater storage over 2003-2021. **Source**: Li et al. (2019)[81] **Persistent web link**: http://doi.org/10.5067/IIU5JWU2AGRP **Temporal range**: 2003-2021 **Spatial resolution**: 0.25 degrees **Resolution harmonization method**: Nearest neighbour resampling **Additional preprocessing**: None
Change in extreme rainfall	**Rationale**: Importance of episodic groundwater recharge during extreme rainfall events[82,83]. **Indicator**: Relative change in the annual frequency of 10mm d^{-1} precipitation events between 1980-1989 and 2010-2019. **Source**: MSWEP; Beck et al. (2019)[84] **Persistent web link**: https://www.gloh2o.org/mswep/ **Temporal range**: 2010-2019 relative to 1980-1989 **Spatial resolution**: 0.1 degrees **Resolution harmonization method**: Nearest neighbour resampling **Additional preprocessing**: Daily precipitation data for the two time windows listed above were processed for the frequency of days exceeding 10mm/d. Relative changes were clipped to a maximum of 100% to limit the influence of extreme values on SOM classification results.
Land use change	**Rationale**: Land use change is a direct driver of change in groundwater recharge[60], and modern groundwater, the groundwater most vulnerable to global change, is evaluated as groundwater that has recharged within 50 years[85]. **Indicator**: Relative change in urban, cropland, and pasture classes of land use from 1960-1969 to 2010-2019. **Source**: Winkler et al. (2021)[86] **Persistent web link**: https://doi.org/10.1594/PANGAEA.921846 **Temporal range**: Land use in 2015 relative to 1960 **Spatial resolution**: 0.01 degrees **Resolution harmonization method**: Area-weighted fraction

	Additional preprocessing: Urban, cropland, and pasture/rangeland calculated as proportion to total grid cell area. Thus forest, unmanaged grass/shrubland, sparse/no vegetation, and water land uses are not considered. Relative changes were clipped to a maximum of 100% to limit the influence of extreme values on SOM classification results.
Agricultural intensification	**Rationale**: Agriculture represents the largest sectoral user of groundwater, and agricultural intensification to close yield gaps poses a parallel threat to cropland expansion to drive increased agricultural water use. **Indicator**: Yield gaps averaged across 10 major crops for the year 2010 **Source**: Gerber et al. (2024)[87] **Persistent web link**: https://doi.org/10.5281/zenodo.10234041 **Temporal range**: circa 2010 **Spatial resolution**: 5 arcminute **Resolution harmonization method**: None **Additional preprocessing**: None
Unmet conservation needs	**Rationale**: Groundwater supports groundwater-dependent ecosystems around the world[88], and groundwater management is crucial to ensure the function of these ecosystems and their services[89]. **Indicator**: Prioritization index for conserving terrestrial biodiversity, carbon, and water considering current extents of protected areas, circa 2020. **Source**: Jung et al. (2021)[90] **Persistent web link**: https://doi.org/10.5281/zenodo.5006332 **Temporal range**: circa present **Spatial resolution**: 10 km (Mollweide projection) **Resolution harmonization method**: Bilinear resampling **Additional preprocessing**: None
Hydro-political conflict	**Rationale**: Groundwater depletion is linked with social conflicts, from tensions within communities to acting as a contributing trigger for conflict, underscoring the need to manage groundwater as a tool for peace and cooperation. **Indicator**: Indicator of hydro-political risk over 1997-2012 **Source**: Farinosi et al. (2018)[91] **Persistent web link**: Provided by author. **Temporal range**: 1997-2012 **Spatial resolution**: 0.25 degrees **Resolution harmonization method**: Nearest neighbour resampling **Additional preprocessing**: None
Gender development inequalities	**Rationale**: Improved water access can act as a tool to reduce gender inequalities in regions where women spend disproportionately more time collecting water than men[92], and has cascading impacts on education and women empowerment[93]. **Indicator**: Subnational Gender Development Index for the year 2020 **Source**: Global Data Lab **Persistent web link**: https://globaldatalab.org/shdi/ **Temporal range**: 2020 **Spatial resolution**: Subnational regions **Resolution harmonization method**: Rasterization to 5 arcminute grids **Additional preprocessing**: None

Change in water crowding	**Rationale**: Population growth corresponds with greater domestic and agricultural demand for freshwater resources and creates opportunities for further inequalities following greater competition for freshwater access. **Indicator**: Relative population change from 2020 to 2050 under SSP3 **Source**: Wang et al. (2022)[94] **Persistent web link**: https://doi.org/10.6084/m9.figshare.19608594.v2 **Temporal range**: 2020, 2050 (SSP3) **Spatial resolution**: 30 arcsecond **Resolution harmonization method**: Summation aggregation **Additional preprocessing**: None

Main text and methods references

1. Closas, A. & Villholth, K. G. Groundwater governance: Addressing core concepts and challenges. *WIREs Water* **7**, e1392 (2020).
2. Curran, D., Gleeson, T. & Huggins, X. Applying a science-forward approach to groundwater regulatory design. *Hydrogeol J* **31**, 853–871 (2023).
3. Nelson, R. L. Water rights for groundwater environments as an enabling condition for adaptive water governance. *Ecology and Society* **27**, (2022).
4. Ostrom, E. Design principles in long-enduring irrigation institutions. *Water Resour. Res.* **29**, 1907–1912 (1993).
5. *Villholth, K. G., López-Gunn, E., Conti, K. I., Garrido, A. & Van der Gun, J. (eds.) Advances in Groundwater Governance. (CRC Press/Balkema, Leiden, The Netherlands, 2018).*
6. Aeschbach-Hertig, W. & Gleeson, T. Regional strategies for the accelerating global problem of groundwater depletion. *Nature Geosci* **5**, 853–861 (2012).
7. Balasubramanya, S. *et al.* Risks from solar-powered groundwater irrigation. *Science* **383**, 256–258 (2024).
8. Devineni, N., Perveen, S. & Lall, U. Solving groundwater depletion in India while achieving food security. *Nat Commun* **13**, 3374 (2022).
9. Swaraj, A. & Maheshwari, B. Understanding the role of groundwater in the lives of rural women in India. *World Water Policy* **8**, 116–131 (2022).
10. De Stefano, L. & Lopez-Gunn, E. Unauthorized groundwater use: institutional, social and ethical considerations. *Water Policy* **14**, 147–160 (2012).
11. Navedo, J. G., Piersma, T., Figuerola, J. & Vansteelant, W. Spain's Doñana World Heritage Site in danger. *Science* **376**, 144 (2022).
12. Acreman, M. & Salathe, T. A complex story of groundwater abstraction and ecological threats to the Doñana National Park World Heritage Site. *Nat Ecol Evol* **6**, 1401–1402 (2022).
13. Ruzzante, S. W. & Gleeson, T. Rising Temperatures Drive Lower Summer Minimum Flows Across Hydrologically Diverse Catchments in British Columbia. *Water Resources Research* **61**, e2024WR038057 (2025).
14. Curran, D. Indigenous Processes of Consent: Repoliticizing Water Governance through Legal Pluralism. *Water* **11**, 571 (2019).

15. Foster, S., Hirata, R., Vidal, A., Schmidt, G. & Garduño, H. *The Guarani Aquifer Initiative – Towards Realistic Groundwater Management in a Transboundary Context*. World Bank, GW•MATE Case Profile Collection (2009).
16. Hirata, R., Kirchheim, R. E. & Manganelli, A. Diplomatic Advances and Setbacks of the Guarani Aquifer System in South America. *Environmental Science & Policy* **114**, 384–393 (2020).
17. Abidin, H. Z., Andreas, H., Gumilar, I. & Brinkman, J. J. Study on the risk and impacts of land subsidence in Jakarta. in *Proceedings of IAHS* vol. 372 115–120 (Copernicus GmbH, 2015).
18. Famiglietti, J. S. The global groundwater crisis. *Nature Clim Change* **4**, 945–948 (2014).
19. Lall, U., Josset, L. & Russo, T. A Snapshot of the World's Groundwater Challenges. *Annual Review of Environment and Resources* **45**, 171–194 (2020).
20. Gorelick, S. M. & Zheng, C. Global change and the groundwater management challenge. *Water Resources Research* **51**, 3031–3051 (2015).
21. Giordano, M. *Global Groundwater? Issues and Solutions. Annu. Rev. Environ. Resour.* **34**, 153–178 (2009).
22. Gleeson, T., Cuthbert, M., Ferguson, G. & Perrone, D. Global Groundwater Sustainability, Resources, and Systems in the Anthropocene. *Annual Review of Earth and Planetary Sciences* **48**, 431–463 (2020).
23. Scanlon, B. R. *et al.* Global water resources and the role of groundwater in a resilient water future. *Nat Rev Earth Environ* **4**, 87–101 (2023).
24. Kuang, X. *et al.* The changing nature of groundwater in the global water cycle. *Science* **383**, eadf0630 (2024).
25. Jasechko, S. *et al.* Rapid groundwater decline and some cases of recovery in aquifers globally. *Nature* **625**, 715–721 (2024).
26. Richey, A. S. *et al.* Quantifying renewable groundwater stress with GRACE. *Water Resources Research* **51**, 5217–5238 (2015).
27. Konikow, L. F. Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophysical Research Letters* **38**, (2011).
28. Chandanpurkar, H. A. *et al.* Unprecedented continental drying, shrinking freshwater availability, and increasing land contributions to sea level rise. *Science Advances* **11**, eadx0298 (2025).
29. Jasechko, S. & Perrone, D. Global groundwater wells at risk of running dry. *Science* **372**, 418–421 (2021).
30. de Graaf, I. E. M., Gleeson, T., (Rens) van Beek, L. P. H., Sutanudjaja, E. H. & Bierkens, M. F. P. Environmental flow limits to global groundwater pumping. *Nature* **574**, 90–94 (2019).
31. Rohde, M. M. *et al.* Groundwater-dependent ecosystem map exposes global dryland protection needs. *Nature* **632**, 101–107 (2024).
32. Global Groundwater Statement. Global Groundwater Sustainability: A Call to Action. https://www.groundwaterstatement.org/ (2019).
33. Domínguez-Guzmán, C., Zwarteveen, M. & Kuper, M. Transformation as Practice: Learning From Everyday Dealings With Groundwater. *Water Alternatives* **16**, 1-12 (2023).
34. Linton, J. What Is Water? *UBC Press* https://www.ubcpress.ca/what-is-water (2010).
35. Zwarteveen, M. *et al.* Transformations to groundwater sustainability: from individuals and pumps to communities and aquifers. *Current Opinion in Environmental Sustainability* **49**, 88–97 (2021).

36. Foster, S., Chilton, J., Nijsten, G.-J. & Richts, A. Groundwater—a global focus on the 'local resource'. *Current Opinion in Environmental Sustainability* **5**, 685–695 (2013).
37. Moore, M.-L. *et al.* Moving from fit to fitness for governing water in the Anthropocene. *Nat Water* **2**, 511–520 (2024).
38. Dalin, C., Wada, Y., Kastner, T. & Puma, M. J. Groundwater depletion embedded in international food trade. *Nature* **543**, 700–704 (2017).
39. Rittel, H. W. J. & Webber, M. M. Dilemmas in a general theory of planning. *Policy Sci* **4**, 155–169 (1973).
40. Huggins, X. *et al.* Groundwater Connections and Sustainability in Social-Ecological Systems. *Groundwater* **61**, 463–478 (2023).
41. Funtowicz, S. O. & Ravetz, J. R. Science for the post-normal age. *Futures* **25**, 739–755 (1993).
42. Huggins, X., Gleeson, T., Villholth, K. G., Rocha, J. C. & Famiglietti, J. S. Groundwaterscapes: A Global Classification and Mapping of Groundwater's Large-Scale Socioeconomic, Ecological, and Earth System Functions. *Water Resources Research* **60**, e2023WR036287 (2024).
43. Huggins, X. *et al.* A review of open data for studying global groundwater in social–ecological systems. *Environ. Res. Lett.* **20**, 093002 (2025).
44. Keys, P. W. *et al.* Anthropocene risk. *Nat Sustain* **2**, 667–673 (2019).
45. Schellnhuber, H.-J. *et al.* Syndromes of Global Change. *GAIA* **6**, 19–34 (1997).
46. Oberlack, C. *et al.* Archetype analysis in sustainability research: meanings, motivations, and evidence-based policy making. *Ecology and Society* **24**, (2019).
47. Riggio, J. *et al.* Global human influence maps reveal clear opportunities in conserving Earth's remaining intact terrestrial ecosystems. *Global Change Biology* **26**, 4344–4356 (2020).
48. Newig, J., Challies, E., Cotta, B., Lenschow, A. & Schilling-Vacaflor, A. Governing global telecoupling toward environmental sustainability. *Ecology and Society* **25**, (2020).
49. Schmidt, J. J. From integration to intersectionality: A review of water ethics. *Water Alternatives* **16**, (2023).
50. Schmidt, J. J. & Peppard, C. Z. Water ethics on a human-dominated planet: rationality, context and values in global governance. *WIREs Water* **1**, 533–547 (2014).
51. Loring, P. A. Threshold concepts and sustainability: features of a contested paradigm. *FACETS* **5**, 182–199 (2020).
52. Molle, F. & Closas, A. Groundwater metering: revisiting a ubiquitous 'best practice'. *Hydrogeol J* **29**, 1857–1870 (2021).
53. Pahl-Wostl, C., Lebel, L., Knieper, C. & Nikitina, E. From applying panaceas to mastering complexity: Toward adaptive water governance in river basins. *Environmental Science & Policy* **23**, 24–34 (2012).
54. *Well Labs.* https://welllabs.org/
55. *T2SGS: Transformations to Groundwater Sustainability.* https://t2sresearch.org/project/t2sgs/.
56. *CLARITY project.* https://clareprogramme.org/project/climate-adaptation-and-resilience-in-tropical-drylands-clarity/.
57. Reinecke, R., Pianosi, F. & Wagener, T. How to use the impossible map – Considerations for a rigorous exploration of Digital Twins of the Earth. *Socio-Environmental Systems Modelling* **6**, 18786 (2024).

58. Winter, T. The Concept of Hydrologic Landscapes1. *Journal of the American Water Resources Association* **37**, 335–349 (2001).
59. Meyfroidt, P. *et al.* Middle-range theories of land system change. *Global Environmental Change* **53**, 52–67 (2018).
60. Scanlon, B. R., Reedy, R. C., Stonestrom, D. A., Prudic, D. E. & Dennehy, K. F. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology* **11**, 1577–1593 (2005).
61. Wada, Y., van Beek, L. P. H. & Bierkens, M. F. P. Nonsustainable groundwater sustaining irrigation: A global assessment. *Water Resources Research* **48**, (2012).
62. Jones, K. R. *et al.* One-third of global protected land is under intense human pressure. *Science* **360**, 788–791 (2018).
63. Almer, C., Laurent-Lucchetti, J. & Oechslin, M. Water scarcity and rioting: Disaggregated evidence from Sub-Saharan Africa. *Journal of Environmental Economics and Management* **86**, 193–209 (2017).
64. Kløve, B. *et al.* Groundwater dependent ecosystems. Part I: Hydroecological status and trends. *Environmental Science & Policy* **14**, 770–781 (2011).
65. Cuthbert, M. O. *et al.* Global patterns and dynamics of climate–groundwater interactions. *Nature Clim Change* **9**, 137–141 (2019).
66. Konikow, L. F. & Kendy, E. Groundwater depletion: A global problem. *Hydrogeol J* **13**, 317–320 (2005).
67. Delgado, S., Higuera, C., Calle-Espinosa, J., Morán, F. & Montero, F. A SOM prototype-based cluster analysis methodology. *Expert Systems with Applications* **88**, 14–28 (2017).
68. Strehl, A. & Ghosh, J. Cluster Ensembles – A Knowledge Reuse Framework for Combining Multiple Partitions. *Journal of Machine Learning Research* **3**, 583–617 (2002).
69. LaGro, J. Assessing Patch Shape in Landscape Mosaics. *Photogrammetric Engineering & Remote Sensing* **57**, 285–293 (1991).
70. Hesselbarth, M. H. K., Sciaini, M., With, K. A., Wiegand, K. & Nowosad, J. landscapemetrics: an open-source R tool to calculate landscape metrics. *Ecography* **42**, 1648–1657 (2019).
71. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria (2025). https://www.R-project.org/
72. Wehrens, R. & Kruisselbrink, J. Flexible Self-Organizing Maps in kohonen 3.0. *Journal of Statistical Software* **87**, 1–18 (2018).
73. Boelaert, J. *et al.* aweSOM: Interactive Self-Organizing Maps. (2022).
74. Walesiak, M. & Dudek, A. The Choice of Variable Normalization Method in Cluster Analysis. in *Education Excellence and Innovation Management: A 2025 Vision to Sustain Economic Development During Global Challenges* (2020).
75. Hausser, J. & Strimmer, K. Entropy Inference and the James-Stein Estimator, with Application to Nonlinear Gene Association Networks. *Journal of Machine Learning Research* **10**, 1469–1484 (2009).
76. Hijmans, R. J. *et al.* terra: Spatial Data Analysis. (2022).
77. Tennekes, M. tmap: Thematic maps in R. *J. Stat. Softw.* **84**, 1–39 (2018).
78. Wickham, H. *ggplot2*. (Springer International Publishing, Cham, 2016). doi:10.1007/978-3-319-24277-4.
79. Mills, B. R. MetBrewer: Color Palettes Inspired by Works at the Metropolitan Museum of Art. (2022).

80. Herrera-García, G. *et al.* Mapping the global threat of land subsidence. *Science* **371**, 34–36 (2021).
81. Li, B. *et al.* Global GRACE Data Assimilation for Groundwater and Drought Monitoring: Advances and Challenges. *Water Resources Research* **55**, 7564–7586 (2019).
82. Taylor, R. G. *et al.* Ground water and climate change. *Nature Clim Change* **3**, 322–329 (2013).
83. Owor, M., Taylor, R. G., Tindimugaya, C. & Mwesigwa, D. Rainfall intensity and groundwater recharge: empirical evidence from the Upper Nile Basin. *Environ. Res. Lett.* **4**, 035009 (2009).
84. Beck, H. E. *et al.* MSWEP V2 Global 3-Hourly 0.1° Precipitation: Methodology and Quantitative Assessment. *Bulletin of the American Meteorological Society* **100**, 473–500 (2019).
85. Gleeson, T., Befus, K. M., Jasechko, S., Luijendijk, E. & Cardenas, M. B. The global volume and distribution of modern groundwater. *Nature Geosci* **9**, 161–167 (2016).
86. Winkler, K., Fuchs, R., Rounsevell, M. & Herold, M. Global land use changes are four times greater than previously estimated. *Nat Commun* **12**, 2501 (2021).
87. Gerber, J. S. *et al.* Global spatially explicit yield gap time trends reveal regions at risk of future crop yield stagnation. *Nat Food* **5**, 125–135 (2024).
88. Saccò, M. *et al.* Groundwater is a hidden global keystone ecosystem. *Global Change Biology* **30**, e17066 (2024).
89. Saito, L. *et al.* Managing Groundwater to Ensure Ecosystem Function. *Groundwater* **59**, 322–333 (2021).
90. Jung, M. *et al.* Areas of global importance for conserving terrestrial biodiversity, carbon and water. *Nat Ecol Evol* **5**, 1499–1509 (2021).
91. Farinosi, F. *et al.* An innovative approach to the assessment of hydro-political risk: A spatially explicit, data driven indicator of hydro-political issues. *Global Environmental Change* **52**, 286–313 (2018).
92. UNESCO. *The United Nations World Water Development Report 2016: Water and Jobs.* https://unesdoc.unesco.org/ark:/48223/pf0000243938 (2016).
93. Kookana, R. S. *et al.* Groundwater scarcity impact on inclusiveness and women empowerment: Insights from school absenteeism of female students in two watersheds in India. *International Journal of Inclusive Education* **20**, 1155–1171 (2016).
94. Wang, X., Meng, X. & Long, Y. Projecting 1 km-grid population distributions from 2020 to 2100 globally under shared socioeconomic pathways. *Sci Data* **9**, 563 (2022).