A review of open data for studying global groundwater in social-ecological systems

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Abstract

Global data have served an integral role in characterizing large-scale groundwater systems, identifying their sustainability challenges, and informing on socioeconomic and ecological dimensions of groundwater. These insights have revealed groundwater as a dynamic component of both the water cycle and social-ecological systems, leading to an expansion in groundwater science that increasingly focuses on interactions between groundwater with ecological, socioeconomic, and Earth systems. This shift presents many opportunities that are conditional on broader, more interdisciplinary system conceptualizations, models, and methods that require the integration of a greater diversity of data in contrast to conventional hydrogeological investigations. Here, we catalogue 144 global open access datasets and dataset collections relevant to groundwater science that span elements of the hydrosphere, biosphere, atmosphere, lithosphere, food systems, governance, management, and other socioeconomic system dimensions. The assembled catalogue offers a reference of existing data for use in interdisciplinary assessments, and we summarize these data across their primary system, spatial resolution, temporal range, data type, generation method, level of groundwater representation, and institutional location of lead authorship. The catalogue includes 15 groundwater datasets, 23 datasets explicitly linked with groundwater, and 106 datasets with implicit or potential groundwater connections. We find the majority of datasets are temporally static and that temporally dynamic data availability currently peaks during the 2000-2010 decade. Only a small fraction of temporally dynamic data are explicitly linked to groundwater, representing a significant opportunity for future work to address. We find that most groundwater datasets are generated by a small number of countries, including the USA, Germany, the Netherlands, and Canada. We raise three themes of possible priorities for future global groundwater data initiatives, which include: data improvements through more explicit integration of groundwater and prioritizing observed and temporally dynamic data; elevating regional and local scale data and perspectives to address challenges relating to equity and bias; and advancing and promoting data sharing initiatives founded on reciprocal benefits between global initiatives and data providers.

1. Introduction

Groundwater, a critical resource for drinking water, agriculture, and ecosystems, is under increasing pressure from human activities and climate change (Famiglietti 2014, Abbott *et al* 2019, Gleeson *et al* 2020, Kuang *et al* 2024, Scanlon *et al* 2023, Jasechko *et al* 2024, Reinecke *et al* 2024, Taylor *et al* 2013, Bierkens and Wada 2019). Recognizing groundwater connections in social-ecological systems has been proposed as a more holistic approach to address the complexities of groundwater's evolving role in the Anthropocene and support equitable groundwater management (Huggins *et al* 2023, Kuang *et al* 2024). Applying this understanding requires a broader conceptualization where hydrogeological systems are not understood as stand-alone resource systems but rather as systems embedded within a network of socioeconomic, ecological, and Earth systems (Gleeson and Cardiff 2013, Huggins *et al* 2023). This conceptual extension of groundwater systems to a more holistic social-ecological model is supported by both groundwater and social-ecological systems theory (Berkes *et al* 1998, Zellner

2008) and implicitly by a wide and yet unquantified variety and volume of data. Understanding the scope of data available to study groundwater in social-ecological systems is necessary to inform data generation and sharing priorities, and more broadly support theory development of groundwater in the Anthropocene.

There is a long history of scholarship on groundwater as a common-pool resource (Ostrom 1990, Blomquist *et al* 1994), and there is a rich literature detailing the benefits of applying social-ecological system framings to understand groundwater within social, economic, human, and ecological contexts (Rica *et al* 2017, Barreteau *et al* 2016, Bouchet *et al* 2019). The recent groundwater-connected systems framing (Huggins *et al* 2023), which identifies and details groundwater systems and processes across elements of the Social-Ecological Systems Framework (McGinnis and Ostrom 2014), provides the thematic scope of this review. Whereas conventional groundwater investigations typically integrate hydrogeological, climatic, and topographic data (e.g., hydraulic conductivity, precipitation, and land surface elevation), assessments of social-ecological systems require an integrated consideration of biophysical and social systems that extend beyond this scope to include data on ecosystems, governance, economic activity, and the broader socioeconomic context (e.g., environmental flows, groundwater institutions, groundwater irrigation, and human development). This social-ecological framing is centered on groundwater interactions with connected systems and thus foregrounds groundwater's diverse roles in systems such as the Earth system (Gleeson *et al* 2020), human health (Wang *et al* 2023), food systems (Siebert *et al* 2010, Dalin *et al* 2019) and cultures (Re 2015, Zwarteveen *et al* 2021). We aim to capture existing open data availability across all of these systems as they relate to groundwater in this review.

Groundwater-connected systems operate across a range of scales from the local to the global: stream-aquifer interactions at the reach scale (Brunner 2017, Yang *et al* 2025), basin scale management agencies and actions (e.g., Groundwater Sustainability Agencies in California, USA), groundwater-dependent ecosystems sustained by regional groundwater flow (Aldous and Gannett 2021, Yao *et al* 2018), transboundary aquifer governance (Shaminder and Villholth 2017), international virtual water trade networks (Dalin *et al* 2017), and climate change drivers of regional groundwater storage (Wu *et al* 2020). In recognition of the interconnectedness between these processes and the widespread nature of groundwater challenges, a global research agenda on groundwater has emerged over recent decades (Konikow 2005, Foster *et al* 2013, Giordano 2009, Gleeson *et al* 2020; Kuang *et al* 2024) that is rooted in the development of global sustainability frameworks and enabled by growth in data and computational methods and abilities. To support this agenda, we focus this review on data with global spatial coverage. This focus on data with global coverage is tailored to support analyses on systematic comparison between regions, Earth system processes and interactions with groundwater (Gleeson *et al* 2020), evaluation or validation of continental and global models (Gleeson *et al* 2021, Gnann *et al* 2023), and to mirror the extent of the broader global groundwater sustainability discourse (Famiglietti, 2014, Gleeson *et al* 2020; Scanlon *et al* 2023, Mukherjee 2024). Furthermore, these global datasets can be used as place-holder data in regions where localized data are either unavailable or of insufficient quality.

Here, we assemble and review a large catalogue of open-access datasets to support this growing global research agenda on groundwater in social-ecological systems. Open science is “perhaps the most important paradigm shift in the recent history of scholarly publishing” (Clark *et al* 2021) through its democratization of information access and its promotion of transparency and reproducibility, among other benefits. Thus, we limit our review to open access datasets to align this work with the open science movement and to encourage the open sharing of global datasets in future work. While we focus on global data, we note that these data can represent processes that operate across a variety of spatial and temporal scales. To review the catalogue, we derive a wide variety of metadata including the primary system to which the dataset relates, the dataset’s spatial resolution, temporal range, level of groundwater representation, data generation method and data format.

This review of global data doubles as an opportunity to assess geographic trends in institutional data authorship. Clear biases towards institutions in the global North have been identified in climate, environmental, and conservation sciences (Karlsson *et al* 2007; Maas *et al* 2021, Hazlett *et al* 2020), and for study areas of hydrological climate hazards (Stein *et al* 2024). Similar biases have been recently identified for groundwater modelling regarding model extents and with respect to non-local model development (Zamrsky *et al* 2025), however these forms of bias have yet to be explored and discussed with respect to global groundwater data. Understanding which regions are driving global groundwater data development, including the coordination of global data sharing initiatives, can be instructive to evaluate representation of regional values and needs in these processes. Further, this analysis can be used as a basis to explore potential opportunities and tensions between global groundwater data ambitions and local to regional datasets, priorities, and realities.

Summarizing metadata across the compiled data catalogue enables the research questions listed below to be investigated. After reviewing these outcomes, we discuss a suite of needs and priorities for future groundwater data efforts that address identified limitations and opportunities.

- How many global datasets and dataset collections are openly accessible for studying groundwater in social-ecological systems?
- What is the distribution of datasets across social-ecological system elements, and is this distribution balanced or biased toward certain elements?
- How many datasets are temporally static, and how many are temporally dynamic?
- What are the spatial (e.g., grid size or zonal unit) and temporal (e.g., time step) resolutions of these datasets?
- How explicitly is groundwater represented or integrated in dataset generation?
- What is the national distribution of institutional authorship of these datasets, and how does this distribution compare and relate to regional trends in groundwater challenges?

2. Review methodology

2.1 Review intentions

We seek to develop and review a large and representative catalogue of global datasets that are available for the study of groundwater in social-ecological systems. The general approach and structure of our data review is illustrated in Figure 1.

To ensure coverage across social-ecological system elements, we base our review in the groundwater-connected systems framing that conceptualizes groundwater connections with social-ecological systems. However, this framing is nascent and studying groundwater in social-ecological contexts lacks an established self-identifying language and dedicated data repositories. These realities introduce specific complications to our review including decentralized source locations of potential datasets, and ambiguous boundaries.

Regarding dataset identification, we developed a multifaceted approach that considered diverse sources and wide search criteria to locate relevant datasets (described in **2.2 Dataset identification**). Regarding review scope, we were interested in not only identifying data that have already been used to study global groundwater in hydrological and social-ecological system contexts, but also in identifying data that have the potential for such applications. In total, we catalogue datasets with thematic coverage across eight system types, including the hydrosphere, lithosphere, biosphere, atmosphere, food systems, governance, other socioeconomic systems, and an integrative category for datasets that span multiple systems (described in **2.3 Metadata categories**). To fulfill this scope, a considerable amount of data with potential or implicit connections and relevance to groundwater is included in the catalogue. Interpreting these potential and implicit connections to groundwater requires subjective judgements, yet which are unavoidable when engaging with a social-ecological framing (e.g., Andrachuk and Armitage, 2015; Lazurko *et al* 2024). For instance, data on language diversity may offer implicit insights into the local complexity of groundwater governance and management or may provide a proxy representation of the diversity of value systems relating to groundwater. Others, however, may consider such data to hold little relevance for groundwater science.

Our large authorship team of global groundwater, Earth system, and social-ecological system scientists hold a variety of perspectives that are reflected in our assembled catalogue. We thus characterize the catalogue as a large and representative, but not exhaustive, resource. We anticipate that the primary benefit of this initiative will be to serve as a resource for scholars, practitioners, and others to identify data for use in future studies of groundwater in social-ecological systems.

2.2 Dataset identification

We considered multiple sources when identifying datasets for inclusion in this review. We sought to incorporate a wide range of sources to reflect the diverse locations where global geospatial data are hosted online. Thus, we not only searched for datasets generated in publications, but also screened input datasets used in thematically aligned global social-ecological system assessments, leading global geospatial data platforms, compatible global data reviews, and through crowd-sourcing additional inputs from this study's co-authorship. The full list of consulted data sources and screening procedures are reported in Table 1.

Only open-access datasets are included in this review. We take this step to ensure the reviewed datasets are accessible for use in future studies, to encourage data sharing practices, and to broadly align this review with open science principles. In taking this step, this review implicitly evaluates the scope of global groundwater data following *findable* and *accessible* data principles from the FAIR initiative (Wilkinson *et al* 2016). Screening for this criterion biases toward data generated within recent years (ca. 2015 and later) due to the relatively recent rise of open publishing and data deposition practices (Clark *et al* 2021, Hall *et al* 2022). The data sharing agreements for datasets that enable inclusion in this review include Creative Commons licenses, dataset-specific user agreements, or an explicit statement encouraging the use of data where a license or agreement was not readily identifiable.

2.3 Metadata categories

We developed several classification schemes to organize and evaluate datasets. These classifications include: (1) the primary system to which the described dataset relates, (2) how explicitly groundwater is represented in the dataset, (3) dataset type and (4) format, (5) spatial resolution, (6) temporal range and time step for temporally dynamic data, (7) data generation method, and (8) institutional country of lead authorship (Figure 1c).

To classify the primary *system* to which the described variable of each dataset relates, we developed a composite classification scheme that combined elements from social-ecological and Earth system frameworks. This composite scheme was developed to address disciplinary biases in social-ecological and Earth system classifications. Our specification of individual Earth system elements served to counteract the biophysical simplifications in social-ecological system schemes (i.e., atmosphere, biosphere, hydrosphere, and lithosphere data would otherwise be classified under the broad term of biophysical systems). Conversely, elements from the Social-Ecological Systems Framework (SESF; McGinnis and Ostrom, 2014) helped to balance overgeneralized human system representation in Earth system schemes (i.e., governance, food systems, and other socioeconomic dimensions would otherwise be classified under the broad 'Anthroposphere' term). This composite scheme thus consists of eight categories: hydrosphere, lithosphere, biosphere, atmosphere, food systems, governance, other human and socioeconomic systems, and an integrative category for datasets that span multiple systems (Figure 1a). We isolated food systems to reflect the significance of groundwater-agriculture interactions at the global scale, including agriculture representing the dominant driver of groundwater consumption globally, the importance of groundwater for irrigation water supporting crop production and food security, the magnitude of groundwater embedded in international food trade (Siebert *et al* 2010, Wada *et al* 2012, Dalin *et al* 2017), and the large volume of data on food systems in relation to other socioeconomic sectors and human dimensions of groundwater.

To characterize the explicitness of groundwater *representation* in each dataset, we classified all data into one of three orders of representation: direct, explicit, and implicit (Figure 2a). The 'direct' class was assigned to actual groundwater data (e.g., water table depth, groundwater storage, or groundwater temperature), the 'explicit' class was assigned to data that incorporate groundwater in the data generation process (e.g., groundwater-driven wetlands, water table ratio, and groundwater management indicators), and the 'implicit' class was assigned to data that have implied or potential connections to groundwater (e.g., cropland area, freshwater ecoregions, and gross domestic product). We applied a literal approach when assigning explicit versus implicit classes, where data were classified as implicit unless the data generation process included explicit consideration of groundwater. Thus, this procedure to assign orders of groundwater representation is not based on the strength of the underlying theory connecting a variable with groundwater but rather on the dataset generation process itself. For instance, global cropland datasets that do not indicate specific sources of irrigation water were classified as 'implicit' despite agriculture being the dominant consumer of groundwater globally. However, should datasets explicitly consider groundwater, such as identifying areas equipped for groundwater irrigation, these data would be classified as 'explicit'. Similarly, global wetland maps that do not specify wetland type were identified as 'implicit' whereas those that do specify groundwater-dependent wetlands are identified as 'explicit'.

Dataset *types* represent the nature of the dataset as either zonal data (e.g., climate zones), a static dataset (e.g., farm field size for a given date), a time series (e.g., annual population estimates), or event or process records (e.g., international water events such as freshwater treaties or acts of hostility). We assigned data types as 'zonal' if the principal use case is as a spatial unit for data summary (e.g., IPCC reference regions), and as 'static' if the primary use case is the documentation of an underlying system property or attribute (e.g., near-surface porosity), even if a secondary purpose of the data can be as a zonal layer. To differentiate between 'time series' and 'record' classes, we considered time series as data that are provided at regular time steps with a consistent spatial extent whereas historical record data typically have irregular time steps (e.g., water-related conflicts) with potentially inconsistent temporal ranges depending on individual entries within the dataset (e.g., water levels in monitoring wells). Should event records be synthesized into a dataset with regular time steps, these data would be recorded as a time series.

Dataset *formats* were assigned as raster, vector (polygon, polyline, or point), or tabular. For raster data, we recorded the spatial resolution of the dataset. For vector data, we collected dataset-specific spatial information such as the median size of polygons or map scale based on metadata availability. For all temporally dynamic data, we recorded the start and end dates of the series along with the time step if it occurs in regular intervals.

We additionally identified each dataset's *generation method* as being either (1) *in situ* observations, (2) remote sensing observations, or (3) modelled or simulated data, such as datasets that have used statistical or process-based models to extrapolate data across larger domains, historical reconstructions or future projections, or approaches that combine observations with models to develop datasets for variables that are challenging to directly observe.

To assess the geographic distribution of *institutional authorship*, we recorded the country of the institution affiliated with each dataset's lead author. If corresponding and lead authorship differs for a dataset, we additionally included the location of the corresponding author's affiliation. For data with institutions as the data provider, we used the location of the institution's headquarters. When discussing results of these institutional distributions, we limited our analysis to only datasets with direct and explicit groundwater representation to constrain insights and conclusions to the groundwater science community.

2.4 Dataset collections and nomenclature

One challenging aspect of this review concerned how to best incorporate data from large, coordinated research communities such as: output from global hydrological models (Reinecke *et al* 2021; Schellekens *et al* 2017, Warszawski *et al* 2013), precipitation (Sun *et al* 2018), crop systems (Müller *et al* 2019), and other Earth observation datasets (McCabe *et al* 2017, Jaramillo *et al* 2024). These communities have respective data reviews and repositories (see preceding references), and including all associated datasets risked turning our exercise into an intractable 'review of reviews'.

To maintain our focus on reviewing the variety of data available to study global groundwater in social-ecological systems, we use the term 'dataset collection' to indicate when more than one dataset was identified for a specific variable (e.g., precipitation). To ensure that dataset collections did not skew outcomes on data accessibility when summarizing across system types, we count dataset collections as a single dataset when reporting on the overall size of our catalogue (i.e., the size of our catalogue is reported as the count of unique datasets and dataset collections).

We also used the term 'dataset collection' to represent data initiatives that collect a wide variety of variables within the same initiative. For example, the Worldwide Governance Indicators initiative develops six indicators of governance dimensions, yet all indicators are available over the same time range and the same spatial resolution, and are shared as a cohesive dataset. Rather than listing and reporting on these indicators individually, they are included in our review as a single collection.

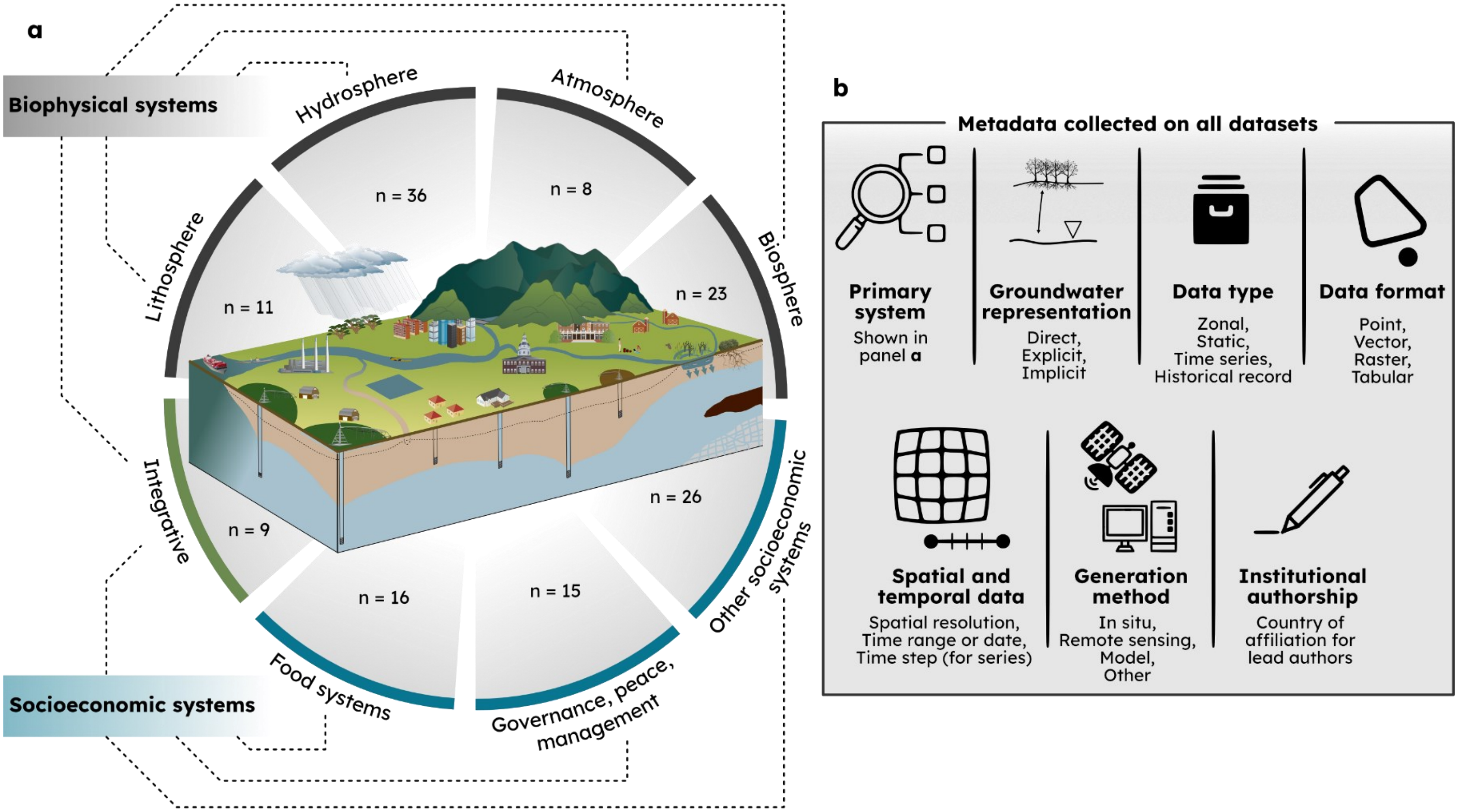

Figure 1. Scope of review. (a) System classification scheme, derived by combining elements from social-ecological and Earth system typologies. The number of unique datasets and dataset collections identified per system (n) are listed in each "slice" of the diagram (e.g., 36 hydrosphere datasets and dataset collections are included in the catalogue). (b) Summary of metadata categories and the possible values they can hold. See Open research section for vector icon attributions.

Table 1. Description of data sources consulted to develop our open data catalogue.

Data source category	Individual sources and how they were screened
Data used in global social-ecological system characterization studies	Ellis and Ramankutty (2008), Gain *et al* (2016), Sietz *et al* (2011), Václavík *et al* (2013), Varis *et al* (2019). → *All input datasets used in each study were screened.*
Global data platforms and compendiums	WRI Aqueduct (https://www.wri.org/aqueduct), WRI Resource Watch (https://resourcewatch.org/), IWRM data portal (https://iwrmdataportal.unepdhi.org/), IGRAC GGIS (https://ggis.un-igrac.org/), WWF Water Risk Filter (https://riskfilter.org/water/home), Protected Planet (https://www.protectedplanet.net/en), MapX (https://unepgrid.ch/en/mapx), GRID-Geneva data platform (https://unepgrid.ch/en/platforms), EarthStat (http://www.earthstat.org/), SEDAC (https://sedac.ciesin.columbia.edu/), Global Human Settlement Layer (GHSL) (https://human-settlement.emergency.copernicus.eu/datasets.php), Global Terrestrial Network - Hydrology (GTN-H) (https://www.gtn-h.info/), Copernicus Land Monitoring Service (https://land.copernicus.eu), Google Earth Engine Data Catalogue (https://developers.google.com/earth-engine/datasets/catalog), Open Land Map compendium (https://openlandmap.github.io/book/012-compendium.html). → *All datasets on each platform with global coverage were screened.*
Compatible global data reviews	Bolognesi *et al* (2018), Lindersson *et al* (2020), Kim *et al* (2021), Wang *et al* (2022). → *All datasets reviewed or summarized in each paper were screened.*

Web of Science search	Searches across the Web of Science core database were performed for the following query strings, and filtered using the “associated data” tag: “biophysical” *AND* “global” *AND* “dataset” (31), “ecological” *AND* “global” *AND* “dataset” (255), “governance” *AND* “global” *AND* “dataset” (36), “groundwater” *AND* “global” *AND* “dataset” (44), “socioeconomic” *AND* “global” *AND* “dataset” (95). Values in parentheses indicate the number of results for each query. All queries were performed in March 2024. *→ All results from the above queries were screened.*

3. Results

3.1 A variety of over a hundred datasets relevant to global groundwater

In total, our catalogue identifies and classifies 144 datasets and dataset collections (Table 2). All datasets, including metadata and persistent web-links are provided in this study’s data repository (repository will be published on Borealis, https://borealisdata.ca/, following manuscript acceptance). An interactive table of the catalogue is accessible on this initiative’s GitHub repository: https://github.com/XanderHuggins/groundwater-SES-data-catalogue.

Table 2. Overview of unique variables and datasets included in the catalogue. The total counts of unique datasets and dataset collections are shown in Figure 2b.

System	**List of variables** * = variable has an associated *dataset collection*
Atmosphere	**Zonal:** Köppen-Geiger climate zones, IPCC reference regions **Static**: Aridity index **Time series**: Precipitation*, Extreme precipitation projections, Evapotranspiration*, Hydrometeorological variable collections **Records:** Isotopes in precipitation, Evapotranspiration observations

Biosphere	**Zonal:** Freshwater and terrestrial ecoregions **Static**: Environmental flow groundwater head limit, Groundwater-dependent ecosystem extents*, Amphibian and mammal species richness, Ecological conservation prioritization index, Global wetlands, Wetlands of International Importance, Groundwater ecosystem biodiversity, Ecohydrological classes of forest growth, Ecosystem functional groups, Root zone storage capacity and depth, Groundwater-driven wetlands, Soil organic carbon content, Ramsar wetlands **Time series**: Vegetation indices* (e.g., NDVI, EVI), Maximum rooting depth, Plant functional types, Ecological vulnerability index, Vegetation health index, Wetland classification, Plant functional types, Dominant classes of grasslands **Records:** Ecosystem fluxes, Species abundances
Lithosphere	**Zonal:** Karst aquifer map, Sedimentary basin map **Static**: Land subsidence, Near-surface permeability and porosity, Sedimentary deposit thickness, Depth to bedrock, Coastal aquifer thickness, Soils, Lithological map, Active faults, Thickness of soil, regolith, and sedimentary deposits, Crust model
Hydrosphere	**Zonal:** Watersheds, River network, Aquifers, Transboundary aquifers, Karst aquifers **Static**: River width, Streamflow indices, Groundwater response time, Modern groundwater volume, River reach fragmentation, Lakes, Lake bathymetry, Lake volumes, River and stream intermittency, Groundwater recharge*, Terrestrial water storage rate of change, Surface water extent, Groundwater vulnerability to floods and droughts, Height above nearest drainage, Coastal aquifer thickness **Time series**: Streamflow*, Soil moisture, Water table depth, Terrestrial water storage anomaly*, Groundwater storage anomaly* **Records:** River discharge, Groundwater levels*, Dam locations and metadata*, Groundwater recharge, Karst spring hydrograph, Isotopes in rivers
Food systems	**Static**: Crop allocation to end uses, Gridded livestock systems*, Crop harvested area*, Crop type, Crop production, Crop yield*, Field size*, Cropland area*, Planting and harvesting dates for major crops, Pasture area, Virtual water trade embedded in agriculture, Area equipped for irrigation by source **Time series**: Yield gaps, Crop water footprints, Irrigated areas*, Cropland extent*, Crop yields*, Harvested areas*, Harvesting dates*, Pesticide and fertilizer application rates

Governance, peace, management	**Zonal:** Administrative units, Indigenous territories, Indigenous treaties **Static**: Environment, social, and governance (ESG) risk index **Time series**: Varieties of democracy, Integrated water resources management implementation indicators, Worldwide governance indicators, Environmental performance index, Subnational corruption, World values survey **Historical records:** Water related intrastate conflict and cooperation, International river basin organizations, International water events, International freshwater treaties, Water conflicts, Water related intrastate conflict or cooperation
Other socioeconomic systems	**Zonal:** Indigenous languages, Protected areas and other effective area-based conservation measures (OECMs) **Static**: Access to improved drinking water, Roads*, Power plants, Accessibility to cities, Development potential indices, Terrestrial human footprint, Relative deprivation index, Travel time to healthcare **Time series**: Freshwater withdrawal by sector, Human modification of terrestrial lands, Human footprint*, Gross domestic product (GDP)* and GDP per capita, Population*, Net migration, Urban land fraction, Human development index, Electricity consumption, Nighttime lights*, Migration*, Gender development inequality, Social adaptive capacity, Gini index, GNI per capita, Human development, Gender inequality **Records:** Managed aquifer recharge schemes, Living conditions of women and well-being
Integrative	**Static**: Population distance to surface freshwater, Land use decision making archetypes, Land system archetypes, Forest and tree proximate people, Human appropriation of net primary productivity **Time series**: Land cover*, Land use change, River basin resilience, Anthropogenic biomes **Records:** World Bank DataBank Indicators, AQUASTAT core database

Of the 144 unique datasets and dataset collections, 15 were classified as direct groundwater data, 23 were explicitly linked to groundwater, and the remaining 106 had an implicit or potential connection to groundwater (Figure 2a). All direct groundwater datasets (e.g., depth to the water table, groundwater storage anomalies, groundwater temperature, etc.) are classified in the hydrosphere category, whereas the 23 datasets with explicit groundwater connections are distributed across all categories but are most commonly represented in the biosphere (e.g., groundwater-dependent ecosystem extents), hydrosphere (e.g., water table ratio), and governance (e.g., management indicators) categories. We find most data with implicit or potential connections to groundwater within the “other socioeconomic systems” category (24), which includes data such as population count, gross domestic product, and gender development inequalities. Trends in groundwater representation vary across the system classes. Half of all hydrosphere datasets directly or explicitly consider groundwater, whereas all other system categories are skewed heavily towards implicit groundwater representation.

Data on hydrosphere systems are the most common in the catalogue (Figure 2b), with 36 datasets and dataset collections. Following the hydrosphere there are other human and socioeconomic systems data (26), biosphere data (23) as these systems that have the greatest variety of accessible datasets. Conversely, lithosphere (11), integrative (9), and atmosphere (8) have the least representation. Governance (15) and food system (16) fall on either side of the median data availability per system class. These patterns in data accessibility may reflect the overall treatment and consideration of groundwater across research fields yet may also simply reflect the scope of individual system categories used in this review (e.g., the class ‘other socioeconomic systems’ is substantially broader than the more constrained ‘atmosphere’ or ‘lithosphere’ classes).

We find several patterns within dataset format, type, and generation method across the system classes (Figure 2b) and which generally reflect methodological differences across disciplines that relate to groundwater. For instance, the majority of governance data is tabular, consists largely of event records (e.g., treaties, conflicts, etc.), and is derived through means outside of in situ observations, remote sensing, and models. Conversely, biophysical data are predominantly raster data, split between static and time series formats, and largely derived through models. Socioeconomic data are predominantly temporally dynamic, whereas the lithosphere datasets are entirely zonal or static.

We find these datasets are most commonly provided at moderate spatial resolutions between 5 and 30 km (Figure 2c). Biosphere data are most common among datasets available at very fine resolutions (<1 km), while socioeconomic data are most commonly available at fine resolutions (1 to 5 km), and food systems at moderate resolutions. The fine resolution is most common among hydrosphere datasets, while national scale data are the most common resolution for governance data.

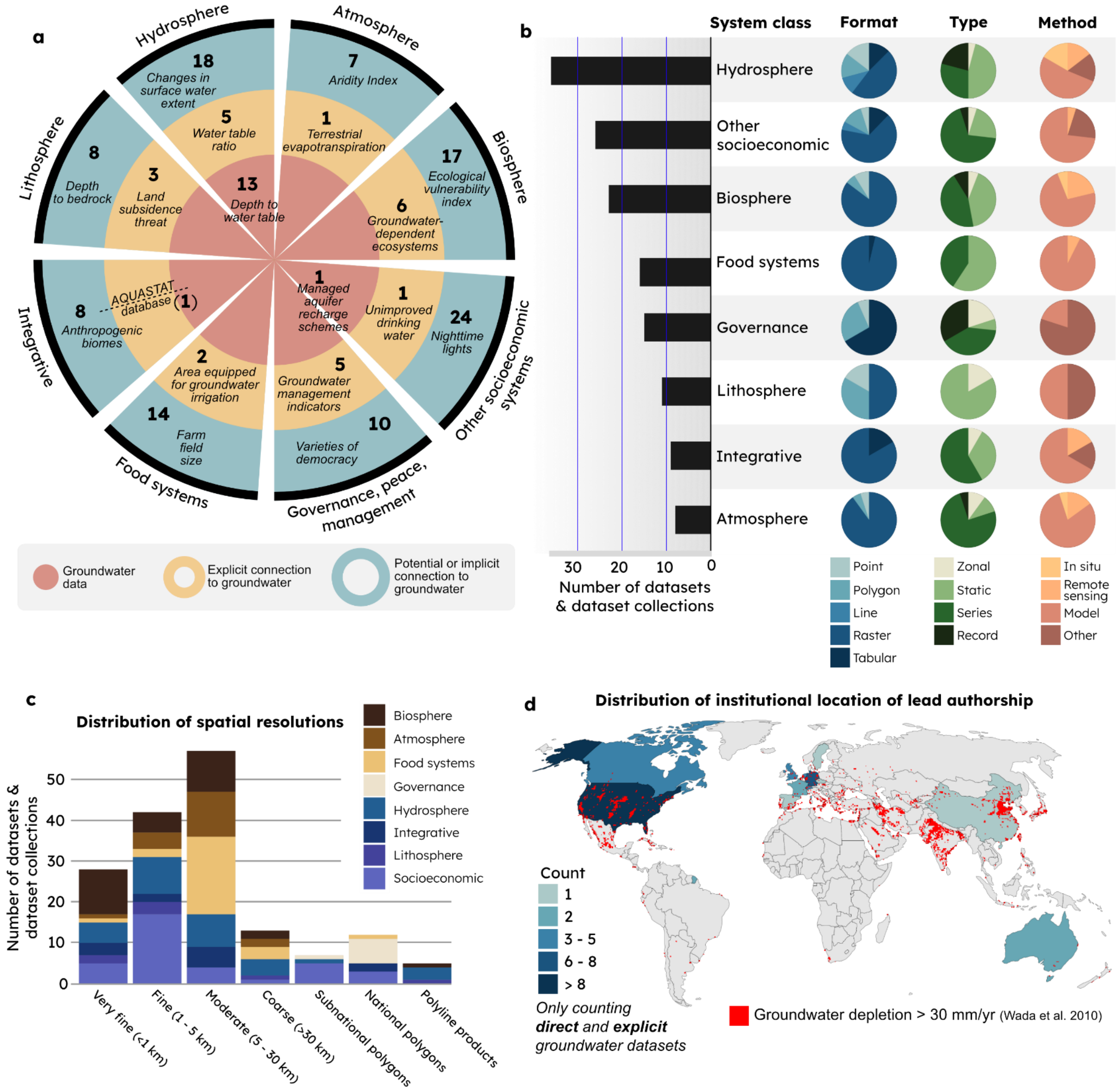

Figure 2. Distribution of reviewed datasets across metadata categories. (a) Dataset count per system class and order of groundwater representation. Example datasets of each class are provided (e.g., *Nighttime lights* for data with implicit connections to groundwater in 'other socioeconomic systems'). (b) Histogram: counts of unique datasets and dataset collections. Pie charts: distributions of metadata categories per system class for all datasets in the catalogue. (c) Distribution of spatial resolutions across system classes for all datasets in the catalogue. (d) Distribution of institutional authorship locations.

3.2 Time series availability and groundwater underrepresentation

We compared temporal ranges of all temporally dynamic datasets across system type, spatial resolution, and groundwater representation (Figure 3). In this comparison, we included record datasets alongside time series datasets when temporal ranges are reported, even if all locations within the record dataset are not available over the full reported range. We find that the greatest overlap among temporally dynamic data to be available over the 2000-2010 decade, peaking with over 80 available datasets. A considerable spike in time series data occurred in 1990 and a consistent decline in time series availability is visible since ~2015. This creates an uncomfortable reality and priority for on-going and future data initiatives: until subsequent datasets are published or updated, there is a greater volume of temporally dynamic data over the 2000-2010 decade than 2010-2020 despite having recently surpassed the mid-point of this century's third decade.

Socioeconomic data represent the most common system class with temporally dynamic data, whereas zero dynamic lithosphere datasets were identified (Figure 3a). Moderate spatial resolutions are the most common within temporally dynamic datasets (Figure 3b). Further, we can observe the emergence of datasets with very fine spatial resolutions in the 1990s. We find very few temporally dynamic datasets that directly and explicitly relate to groundwater (Figure 3c), and thus these time series data largely represent systems with potential or implicit groundwater connections. Only a small subset of time series datasets or dataset collections can be considered actively updated through ongoing efforts.

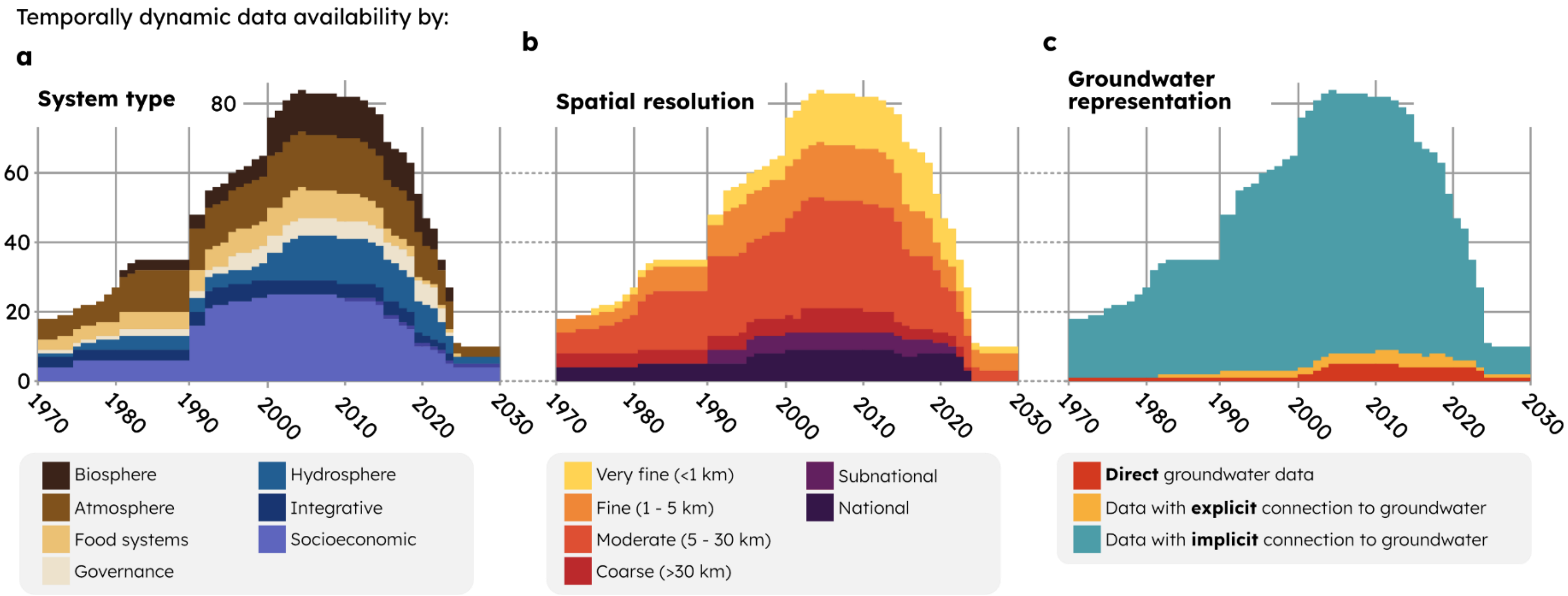

Figure 3: Availability of temporally dynamic datasets. (a) Dataset availability by system type. (b) Dataset availability per spatial resolution. (c) Dataset availability by order of groundwater representation. These plots are generated using the first and last years of available data per dataset and do not represent the time steps of individual datasets. These plots do not group dataset collections together and thus represent temporally dynamic data availability across all datasets in the catalogue.

3.3 Institutional leadership patterns and global North bias

A small set of countries lead the development of these global datasets. Of the datasets with direct or explicit groundwater representation, 10 were led by institutions located in the USA, 8 by institutions located in Germany, and 5 by institutions located in Canada and the Netherlands, respectively (Figure 2d). Only 13 countries have led the development of all 38 datasets (and only 19 countries if extending to all datasets included in our collection). International agencies are responsible for 8 of these direct and explicit groundwater datasets (and are thus not shown in the Figure 2d map). Several countries experiencing severe groundwater sustainability challenges stemming from groundwater depletion, including India, Pakistan, Iran, Mexico, and Japan (Figure 2d), are absent from the institutions generating these global groundwater datasets. South America and Africa are absent from the lead authorship of these global data products, and Australia is the only country represented from the southern hemisphere. Together, this suggests that the processes of generating these global datasets have been overwhelmingly led by institutions from the global North. We reflect on potential implications of this reality in section 4.3.

4. Discussion

Drawing from our review of this global open data landscape, we suggest three themes of potential priorities for global groundwater data (Figure 4). These themes also structure our discussion, with section 4.1 dedicated to the theme “new forms of analysis”, section 4.2 to the theme “new or improved data”, and section 4.3 to the theme “more equitable processes”. Together, these themes correspond with core opportunities and challenges identified in the global data landscape, and are oriented in the spirit of ensuring that global groundwater science and data remain use-inspired and responsive to the evolving needs of researchers, decision-makers and practitioners.

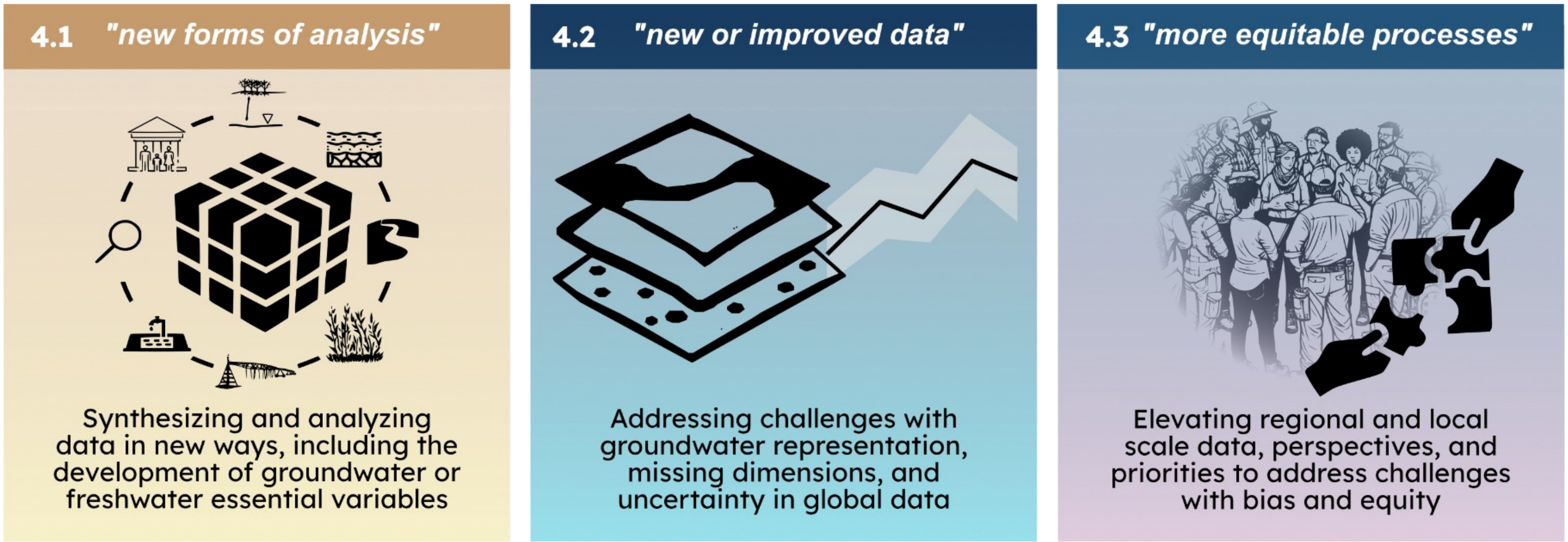

Figure 4. Themes of possible priorities for global groundwater data.
See Open research section for vector icon attributions.

4.1 Existing richness of data with significant potential for synthesis and analysis

Our assembled data catalogue paints a portrait of the open-data landscape supporting the study of groundwater globally in social-ecological systems that is large and diverse. While not formally evaluated by our methodology, our authorship team of global groundwater, Earth system, and social-ecological system scientists shares the perspective that only a small portion of the data included in our assembled catalogue has already been implemented in groundwater-focused studies. In our view, this points to the significant and unrealized potential for social-ecological system mental models, methods, and research objectives in large-scale groundwater science. While we will focus on clear opportunities for improvement in this data landscape (section 4.2), we first seek to emphasize that the research community does not need to wait for greater or improved data availability: rich data are already available. Indeed, combining already existing data may prove to be effective and capable of uncovering new and important relationships between groundwater and social-ecological system elements and processes, and in guiding the identification of which social-ecological data we most urgently lack.

We view the concept of essential variables, such as pursued in the fields of climate (Bojinski *et al* 2014), biodiversity (Pereira *et al* 2013), oceans (Miloslavich *et al* 2018), and ecosystem services (Balvanera *et al* 2022), as one compelling way to integrate a coherent social-ecological framing of groundwater systems with global data and analysis. Essential variables aim to identify a necessary set of variables to sufficiently monitor and detect changes in the function and structure of a given system. In the essential climate variables (ECV) initiative, groundwater is directly included as an ECV and is implicitly represented in the terrestrial water storage variable (GCOS, 2024). Yet, we foresee the potential for a broader and dedicated set of essential variables for groundwater in social-ecological systems, and which could include a subset of the datasets available in our developed data catalogue.

We do not seek to establish a list of essential groundwater variables here as this would necessarily involve a community-wide, iterative, and engaged process. However, we offer a starting point to consider the potential for the groundwater essential variable (GEV) concept. Such an initiative could lead a process of identifying a fundamental and coherent set of groundwater system properties and functions in social-ecological systems that have, or could obtain, observational monitoring or reporting capacities. Further, the initiative could serve the need to harmonize these data into analysis-ready formats, and more broadly could act as a vehicle to organize, develop, synthesize and fund global initiatives on the study of groundwater in social-ecological systems.

4.2 Addressing data limitations including groundwater representation, uncertainty, and blind spots in global data

Our findings also suggest that substantial opportunities and needs exist to improve this data landscape because: all system classes outside of the hydrosphere skew towards datasets with only potential or implicit connections to groundwater, and direct or explicit groundwater data only comprise a small fraction of temporally dynamic datasets. Thus, while there exists substantial potential to apply already available data, the question arises: how can the global-scale groundwater data community make concerted efforts to address these limitations and generate a more extensive and capable global groundwater data landscape?

Using the various classification schemes implemented in our review, we can identify a set of preferences for future data efforts that include: observed over modeled data, time series over static datasets, and explicit consideration or representation of groundwater systems. For instance, datasets on the extents of groundwater-dependent ecosystems and areas equipped for groundwater irrigation are currently available for specific time slices but could offer a myriad of potential insights if both datasets were generated over consistent time ranges (i.e., improving static datasets to time series). There is initial progress in this direction with the generation of a dataset on the temporal evolution of irrigated areas from 1900-1980 in 10-year time steps, and from 1980-2015 in 5-year time steps (Siebert *et al* 2015, Mehta *et al* 2024). However, similar improvements are yet unrealized for groundwater-irrigated areas.

There is also a need to prioritize the development of temporally dynamic datasets. Improving temporal frequency and aligning time steps across existing datasets would significantly improve the scientific potential of these data and would ease the integration of multidimensional data into analysis frameworks. These improvements stand alongside our finding that temporally dynamic data have declined in availability since 2000-2010, and that substantial efforts are needed to generate the same level of data availability for the past decade and decades ahead. We do not necessarily attribute this to a decline in global time series data generation as a time lag is necessary for research efforts to synthesize and publish data covering recent years, particularly for variables and processes that do not benefit from near-real time observational capacities. The decline in temporal data availability may also arise due to reduced incentives, perceived or real, to update and extend existing datasets relative to the incentives of publishing a dataset that is a ‘first of its kind’. Thus, it may be beneficial for groundwater-related societies, journals, and funding agencies to reflect on potential initiatives that can create incentive structures to equitably reward original dataset developers and dataset updaters.

Without sufficient temporally dynamic data, testing hypotheses on dynamic social-ecological system behaviour of groundwater systems such as emergence, tipping points, context dependence, and system resilience (e.g., Preiser *et al* 2018) may be limited to conceptual and theoretical realms (Troy *et al* 2015; Di Baldassere *et al* 2015). These limitations not only create barriers to scientific inquiry but can more problematically impede understanding of complex system dynamics and contribute to erroneous decision making in applied contexts (Chávez García Silva *et al* 2024).

A lack of globally distributed temporally dynamic datasets may point to a future of global groundwater science that is more oriented towards case study and point location-based analyses. These initiatives (e.g., Kreibich *et al* 2023, Tiwari *et al* 2023) may more readily be able to implement existing observational capacities, and may more vividly reflect contextually rich data, such as dimensions of human health or ecosystem services that may be challenging to organize into globally distributed datasets that require common conceptual models and methodologies for monitoring, extrapolation, or modelling over the global domain. Thus, an intermediary level of analysis, consisting of globally distributed case studies integrating groundwater with social-ecological data, may offer pragmatic and instructive insights on both the dynamics of groundwater in social-ecological systems, and to guide future global data initiatives.

There is also a need for data development on currently missing or underrepresented dimensions of groundwater-connected systems. For instance, datasets connecting groundwater with domestic use and human health (e.g., Mukherjee *et al* 2019) such as on health outcomes linked to groundwater salinization (Mueller *et al* 2024), observations on interconnections between groundwater and surface water (e.g., Jasechko *et al* 2021), and that capture human factors such as behavioral (e.g. Castilla-Rho *et al* 2017), economic (e.g., Bierkens *et al* 2024), infrastructural, legal (e.g., Nelson and Perrone 2016, Rohde *et al* 2017), institutional, and governance (e.g., Villholth and Conti 2018) relating to groundwater are particularly rare in the literature.

Several other foundational groundwater datasets would benefit from continued improvement from their original releases. For instance, the development of comprehensive and harmonized geological datasets that combine global lithology maps with global borehole records would enable a cascade of wider dataset improvements including more reliable global groundwater models, improved representation of groundwater in Earth system models, and a strengthened ability to convert observations in groundwater storage to changes in the water table.

Finally, we raise the need for more robust inclusion and reporting of uncertainty in global datasets (Wagener *et al* 2021). Without a systematic practice of uncertainty reporting, dataset selection can be driven by operational convenience, such as ease of integration based on spatial or temporal resolutions, rather than a critical evaluation of data uncertainty and its propagation in derivative analyses. Given social-ecological assessments inherently combine a wide variety of data, reporting on uncertainty becomes all the more important as compounding uncertainties can have important implications on study outcomes that may lead to erroneous or tenuous decision making. Integrating uncertainty in social-ecological data presents additional challenges as uncertainty is often reported in different ways across natural and social sciences (cf. Westerberg *et al* 2017). These challenges aren’t unique to the study of groundwater in social-ecological systems but will be important to address to ensure this interdisciplinary research direction for groundwater science is rigorous, reproducible, and relevant for applied use cases.

4.3 Elevating and respecting regional and local perspectives, priorities, and needs in global initiatives

An abundance of regional and local scale data is missed in this review that is focussed on global data. These range from large, nation-scale initiatives on monitoring wells, groundwater well uses (Lin *et al* 2024), sub-national virtual water flows (Dang *et al* 2015), to a myriad of crowd-sourced data within individual aquifers and basins. Indeed, it should be evident that the volume of global data accumulated in our reviewed catalogue is but a small fraction of the total volume of data that may exist to understand and manage groundwater. Groundwater data needs vary substantially, mirroring the diversity of geographies, ecologies, and societies within which groundwater is situated and connected. Local and regional datasets will inherently correspond better to these needs than those generated through global initiatives. As we focus below on potential avenues to potentially integrate these data into global initiatives, it should be emphasized that local and regional data are essential, relevant, and valuable regardless of their inclusion in global initiatives.

Groundwater and groundwater-connected systems operate across a range of scales, and integrating data generated across a variety of scales is one opportunity to better reflect multi-scalar processes in global datasets. Existing data “networks of networks” such as the Global Groundwater Monitoring Network (IGRAC, 2025) and FLUXNET (Delwiche *et al* 2024), and community initiatives such as the Groundwater Model Portal (Zipper at al., 2023) demonstrate the potential for bottom-up collaboration on global dataset development yet substantial work lies ahead to realize this potential across a wider set of social-ecological dimensions. Involvement of non-governmental organizations, global development organizations, and intergovernmental organizations could play an instrumental role in providing incentives, investment, infrastructure, and/or enforcement (e.g., through strong data mandates) of engagement in global initiatives. However, development of such initiatives is an inherently political process whose success will depend on equitable stakeholder and rightsholder engagement, transparent data-sharing frameworks, and the challenge of ensuring mobilized funding is allocated based on needs (cf. Stein *et al* 2024).

While synthesizing existing regional datasets and initiatives is a laudable goal, it is also one accompanied by substantial challenges. Our observation that global groundwater data are generated and studied in institutions mostly distant from the place- and land-based realities of acute groundwater sustainability challenges raises important questions about what research priorities are driving global scale research and whose interests these priorities primarily serve.

Our aim in highlighting the geographical centers of global data leadership is to encourage reflection on the potential implications of their concentration in the Global North. For instance, recognition of the underrepresentation of scientists from tropical Africa in global climate research has, over the last decade, led to more inclusive research and improved human and infrastructural capacities (e.g. Lamptey *et al* 2024, Senior *et al* 2021) that are now addressing long-held gaps in tropical meteorology and the representation of Africa’s monsoon-dominated climatology in climate projections (WMO, 2022, Senior *et al* 2021)). Similarly, which groundwater connections and uses might we, as a global groundwater community, be underrepresenting in our initiatives?

Thus, data sharing and equitable participation of underrepresented institutions from developing regions are essential components of global data initiatives. However, engagement between local, regional, and global initiatives needs to address long-standing challenges, such as research imbalances and the ownership of scientific advances that are undermined by ‘helicopter’ research (Gbondo and Michelsen, 2024). Developing global data sharing initiatives on the principle of reciprocal benefits will be essential but alone may not be sufficient to address these challenges. Potential benefits to reciprocate the sharing of data from researchers and national or regional agencies may may include increased visibility of data and research (such as through co-authorship on derivative studies), enhanced access to technological capacities for data processing (such as conversion of unprocessed data to standardized formats, data cleanup, and statistical summarizing), and the inclusion and citation of data in global initiatives (e.g., WMO, 2024). However, such benefits will need to be established on a case-by-case basis, tailored to the specific needs of individual data providers, and may require financial commitments for data access to sustain groundwater monitoring programs previously reliant on data access paywalls.

While the above discussion addresses representational biases in global groundwater data generation, it does not resolve broader ethical tensions between Big Data, open science, and Indigenous Data Sovereignty principles (Walter *et al* 2020). Given that as much as 65% of land area is held under Indigenous Peoples' and local community customary systems (RRI, 2015), these are truly global ethical questions and priorities for land-based sciences (Meyfroidt *et al* 2022). In settler-Indigenous contexts and beyond, it is important to ensure that creating open global datasets does not violate the privacy and security of individuals and communities by sharing sensitive information (Zipper *et al* 2019).

Even seemingly innocuous global data such as the type and presence of groundwater-dependent ecosystems may contradict Indigenous Peoples' authority to control data access that follow best practices established in recent data ethics frameworks (Carroll *et al* 2021). Indeed, the Indigenous territories data layer included in our review may be useful for the global groundwater community to better consider how Indigenous issues, priorities, land, and knowledge systems interact with one's work and may inform on how engagement with Indigenous peoples may be necessary to meet ethical standards. Clarifying how the FAIR (findable, accessible, interoperable, reproducible) and CARE (collective benefit, ability to control, responsibility, and Indigenous ethics) data principles (Wilkinson *et al* 2016; Carroll *et al* 2020) interrelate and relate to global groundwater research agendas is thus a critical priority to resolve.

4.4 Review limitations

Our interest in performing a wide sweep of social-ecological systems data for groundwater science applications is a process that requires normative judgements on which data are considered to have potential applications for groundwater studies and will reflect disciplinary biases among our authorship. For instance, our approach is informed by a conceptual groundwater-connected systems perceptual model (Huggins *et al* 2023) that focuses on social-ecological system dynamics in relation to shallow (i.e., upper ~100 m of the subsurface) and terrestrial groundwater systems. This model informs our review scope and thus underrepresents offshore aquifers, deep groundwater systems, and geochemical data. These biases in our catalogue can be addressed through complementary initiatives. While some geochemical datasets are included in our data catalogue, they are principally oriented around human health implications. Our catalogue is thus not a review of groundwater quality and geochemistry datasets (Misstear *et al* 2023), nor does it consider regional datasets that serve important roles in validating global models. Both of these topics warrant separate, dedicated reviews.

Lastly, our analysis of institutional authorship only focused on the affiliations of lead and corresponding authors and did not analyze the full diversity of co-authorship lists. Many of these datasets were developed in large author studies and often do include institutions from lower-resource countries underrepresented in lead authorships. While we view this approach as a pragmatic account of the dominant geographies and institutional contexts of these data generation activities, future work would be welcomed that additionally analyzes the distribution of full authorship lists. Additionally, it would be valuable to analyze the extent to which local-scale data is integrated into global data products and to review the mechanisms through which data providers are acknowledged and included in global data synthesis initiatives.

5 Conclusion

To support continental- to global-scale research on groundwater in social-ecological systems, we developed and reviewed a large catalogue of open-access global datasets and dataset collections (n=144) that directly, explicitly, or implicitly relate to groundwater systems and their social-ecological system interactions. We reveal that a rich variety of data are available for implementation in global studies, and our catalogue can serve as a reference for researchers to locate sources of interdisciplinary data. We also find important limitations and biases in the existing data. At the forefront of these limitations is a lack of temporally dynamic datasets that explicitly represent groundwater, undermining the ability of global groundwater science to generate a strong evidence base for social-ecological system dynamics in relation to groundwater. We also find the institutions leading global dataset generation efforts are overwhelmingly located in the global North, prompting questions about the potential mismatches in needs, interests, and incentives between groundwater data generation and groundwater data needs. We highlight three potential themes for global groundwater data priorities: analyzing existing datasets in new ways to uncover new insights about groundwater in social-ecological systems; generating new or improved datasets to address data limitations including a decline in temporally dynamic data since the 2000-2010 period and a lack of temporally dynamic datasets with explicit groundwater representation; and committing to better, more equitable data generation processes, including providing reciprocal benefits to data providers, elevating local and regional perspectives, needs, and data in global initiatives, and addressing tensions between open science principles with Indigenous data ethics and data privacy. These possible priorities reach widely across the data development environment and call on a variety of actors: researchers to engage more deeply in interdisciplinary groundwater assessments and more inclusively with global co-authors, journals and data repositories to require uncertainty estimates in geospatial data and to incentivize dataset updates equally to original dataset depositions, funding bodies to support research on large-scale groundwater science and data development, and international agencies to providing incentives, investments, and infrastructure in support of global data sharing initiatives.

Open research

The associated collection of datasets, including access links and all collected metadata will be deposited on Borealis (the Canadian Dataverse Repository) upon manuscript acceptance. A copy of this collection is also available on the study's associated repository, available at: https://github.com/XanderHuggins/groundwater-SES-data-catalogue.

All analyses were conducted using the R project for statistical computing (R Core Team, 2023), using the packages *tmap* (Tennekes *et al* 2023), *ggplot2* (Wickham *et al* 2024), and *MetBrewer* (Mills, 2022). Composite figures were assembled in Affinity Designer (https://affinity.serif.com/en-us/designer/).

Figures 1 and 4 use the following icons from Noun Project (https://thenounproject.com/): “give and take” by Alfredo, “collaboration” by Andika Cahya Fitriani, “classification by Sinta Maulana, “groundwater” by Adrien Coquet, “plants” by Hawraa Alsalman, “satellite” and “authorship” by Lufti Gani Al Achmad, “search” by Davindraaja, and the “center pivot irrigation” by Kim Kraeer and Lucy Van Essen-Fishman from the Integration and Application Network (https://ian.umces.edu). Other vector images incorporated in figures were either generated through generative AI (chatGPT by OpenAI) with prompts from the author or were drawn manually in Affinity Designer.

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