Chapter 12
Groundwater sustainability in a digital world

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Abstract

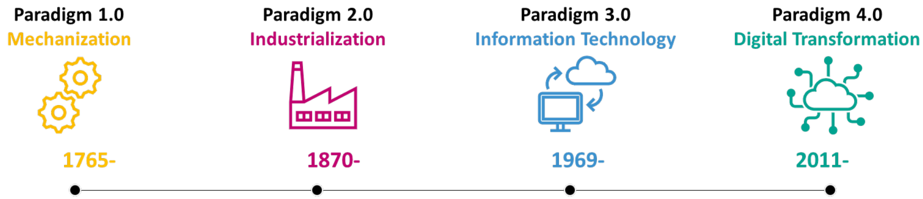
Focused on connectivity and enabled by smart technologies, the fourth industrial revolution is creating a digital transformation that is advancing and prompting sustainable groundwater management practices. Enabled by artificial intelligence, big data, blockchain technology, cloud computing, cyber-physical systems, and the internet-of-things, this digital transformation is creating a paradigm-shift in how we manage our groundwater resources. The next generation groundwater management tools are emerging with web-based groundwater management platforms following the FAIR Data Principles — Findability, Accessibility, Interoperability, and Reusability. These web-based platforms can improve participation, cooperation and collective action, and enable alternative forms of groundwater management such as commons-based peer management of groundwater resources. These web-based platforms not only provide comprehensive and timely information about the groundwater system with simulation and gaming tools, but also enable agents to work cooperatively. In this chapter we discuss groundwater sustainability in a digital world using examples from both developing and developed countries. We show how these web-based platforms can provide historical and future-scenario information for strategic planning and development, and real-time information for daily decision-making. These web-based platforms can additionally facilitate cooperation among groundwater users through a blockchain-based system for groundwater credit, groundwater trading, and groundwater policy incentives, as an example. Furthermore, these we-based platforms do not only inform on groundwater systems, but also can be useful for other smart technologies such as smart agriculture, and smart city. Insights about the prospects of digital groundwater and the anticipated transformation of groundwater management practices are important for researchers, groundwater regulators, groundwater managers, groundwater users, and technology providers to plan for tomorrow.

Keywords: Groundwater sustainability and sustainable groundwater management; hydrology cyberinfrastructure and hydroinformatics; intelligent systems research; digital water and digital groundwater; FAIR Data Principles

1. Introduction

Beneath the Earth's surface, groundwater flows in the pores, fractures, and conduits of the aquifers, which are water-saturated soil and rock formations that contain and transmit significant quantities of water under normal field conditions (Hornberger et al., 2014). Making up more than 97% of the liquid freshwater on Earth, groundwater supplies more than half of the drinking water, approximately 40% of the irrigation water, and about one third of industrial freshwater (UN-Water, 2018). Groundwater is critical for supporting many terrestrial, aquatic and marine groundwater-dependent ecosystems. In addition, groundwater is a manageable buffer to floods, seasonal variations of surface water, and droughts. However, water users' self-interests are leading to the depletion of more than half of the largest aquifers on the Earth, illustrating the tragedy of the commons(Elshall et al., 2021). Groundwater systems are stressed through groundwater over-pumping and by contamination from point and nonpoint sources. Impacts of excessive pumping include the degradation of groundwater-dependent ecosystems, saltwater intrusion, mobilization of heavy metals, and land-subsidence. Without an action, it is now globally recognized that the on-going groundwater over pumping and water quality degradation could transform areas of economic expansion into regions of poverty (Elshall et al., 2021). These adverse impacts call for an action to ensure groundwater sustainability (Gleeson et al., 2019). As a result, major policy reforms have been approved in many countries around the globe (Elshall et al., 2021, 2020) such as the State Water Code of Hawaii (1987), the National Water Act of South Africa (1998), European Union Water Framework Directive (EU-WFD, 2000), National Water Initiative in Australia (2004), Water Sustainability Act in British Columbia (2014), and Sustainable Groundwater Management Act in California (SGMA, 2014). Such policy reforms are crucial for achieving the Sustainable Development Goals (SDGs) of the United Nations' 2030 Agenda, particularly SDG 6 "Clean water and sanitation." Groundwater sustainability is also important for SDG 2 "Zero hunger" through supporting sustainable agriculture, SGD 13 "Climate action" as groundwater is important for mitigating impacts of climate change such as droughts and floods, SDG 14 "Life below water" through supporting marine groundwater dependent ecosystems, and SDG 15 "Life on land " through supporting terrestrial groundwater dependent ecosystems. Groundwater sustainability in a digital world is also important for SDG 11 "Sustainable cities and communities" as digital groundwater can be a main component in smart city.

This chapter discusses how current digital transformation can shape the future of sustainable groundwater management, and contributes to the success of groundwater policy reforms. We are in a period of human history where technological changes are happening at an exponential rate (Roser and Ritchie, 2013). These rapid technological changes are driving the current digital transformation of the fourth industrial revolution, which is characterized by artificial intelligence, big data, cloud computing, cyber-physical systems, internet-of-things, and other smart technologies. Each industrial revolution is characterized by a disruptive technology that creates a shift in how we run the world, leading to changes in the social framework and scientific research as shown in Figure 1. The term *fourth industrial revolution* (a.k.a., 4IR and Industry 4.0) was first introduced by a team of scientists developing a high-tech infrastructure strategy for the government of German in 2011, and was the theme of the World Economic Forum Annual Meeting in 2016 (Schwab, 2016). With respect to scientific research, the reader is referred to Hey et al. (2009) for detail about paradigm shift to the nature of science, and the fourth paradigm of "data-intensive scientific discovery" (Hey et al., 2009). How the digital transformation of the fourth industrial revolution can improve the operationalization of groundwater sustainability policies is the subject of this chapter.



Paradigm-shifter	Steam	Electricity	Computer and internet	Artificial intelligence and internet-of-things
Industrial production	Mechanical production	Assembly line mass production	Automated production	Cyber-physical systems production
Mobility	Steamboat	Railroad	Vehicles, vessels, and aviation	Autonomous vehicles, ships, and drones
Communication	Telegraph	Telephone	Internet	Internet-of-things
Energy	Wood	Coal	Fossil fuel, nuclear, and hydropower	Renewable and zero-carbon sources
Water supply	Water system	Sewage system	Storm drainage system	Sustainable, resilient, and equitable infrastructure
Agriculture	Agricultural revolution	Agricultural mechanization	Agriculture technology	Smart agriculture
Society	Agrarian society	Industrial society	Information society	Digital society
Social change	Revolutions	Human rights	Globalization	Digital-citizen connectivity
Business model	Industrial cities	Industrial regions	Global production network	Commons-based peer production
Science	Empirical description of nature	Theoretical with models and generalization	Computational with complex system simulation	Data intensive scientific discovery and eScience

Figure1. An inexact outline of four industrial revolutions and corresponding paradigms with respect to the society (Schwab, 2016) and scientific research (Hey et al., 2009).

2. Groundwater sustainability

Groundwater sustainability can be defined as “maintaining long-term, dynamically stable storage [and flow] of high-quality groundwater using inclusive, equitable, and long-term governance and management” (Gleeson et al., 2020). As illustrated in Figure 2, evaluating groundwater sustainability considers any combination of multiple aquifer performance and governance, and requires a participation-based multi-process approach with broad uncertainty analysis factors (Elshall et al., 2021, 2020; Pierce et al., 2013).

A basic component of groundwater sustainability evaluation is multi-process modeling (Figure 2). A multi-process approach accounts for the coupled water-ecology-human systems. In the water system, modeling the surface water- groundwater system generally involves the use of mechanistic numerical models (Henriksen et al., 2008), phenomenological models such as analytical functions (Miro and Famiglietti, 2018), and data-driven machine learning models (Salem et al., 2017). With respect to the ecology system, considering ecosystem services of groundwater-dependent ecosystems is generally through defining ecological and ecosystem service targets with indicators and thresholds established for each target. An adaptive management process, which is learning-by-doing, is generally used to update the targets and indicators (Rohde et al., 2020). Although developing predictive groundwater and ecological models to prioritize the most effective management strategies can be challenging, these models are recommended for high-capacity pumping (Saito et al., 2021). The human system focuses on groundwater supply needed for agricultural, municipal, and industrial purposes. Accounting for human activities can be achieved through simple approaches such as pumping projection based on population projection (Urrutia et al., 2018), and recharge projection based on “best-guess” landuse and landcover changes and similar forms of scenario analysis (Bremer et al., 2021). More elaborate approaches include integrated water resources management (Feng et al., 2018), hydro-economic modeling (Mulligan et al., 2014), and socio-hydrology (Castilla-Rho et al., 2019). While integrated water resources management promotes the joint management of water, land, and other natural resources, hydroeconomic modeling aims at optimizing the economic objectives of a water-ecology-human system, and socio-hydrology is a more descriptive approach that integrates human activities as an endogenous component of the water-ecology system (Elshall et al., 2021).

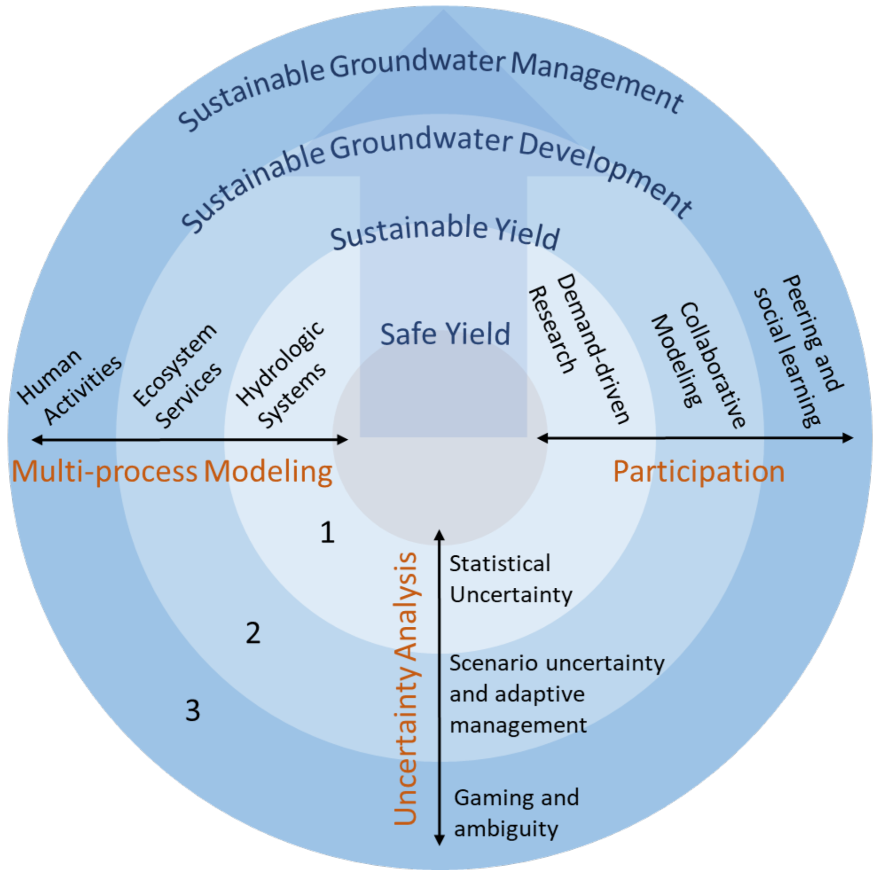


Figure 2. Multi-process modeling, uncertainty analysis, and participation are three basic components of groundwater sustainability evaluation with sphere number reflecting the increasing degree of integration (modified from Elshall et al., 2020).

Modeling tools are advancing to account for coupled water-ecology-human systems. For example, MODFLOW One-Water Hydrologic Flow Model version 2 (MF-OWHM2, Boyce et al., 2020) is an integrated hydrologic model with tight coupling of groundwater, surface water, and vertical unsaturated flows. MF-OWHM2 simulates multiple processes such as landscape processes (e.g., land-use and crop simulation, root uptake of groundwater, and irrigation demand estimation), reservoir operations, aquifer compaction and subsidence, and saltwater intrusion (using sharp-interface). Also, MF-OWHM2 produces a binary flow file for use with MT3DMS and MT3DUSGS for transport simulation in the saturated and unsaturated zones, respectively. GSFLOW (Markstrom et al., 2008; Regan and Niswonger, 2021) couples the Precipitation-Runoff Modeling System (PRMS-V) with MODFLOW-2005 and MODFLOW-NWT, and can be used with the transport models of the MODFLOW family. Wei et al. (2019) present SWAT-MODFLOW-RT3D that tightly couples the semi-distributed watershed model SWAT with the groundwater flow model MODFLOW and the groundwater solute reactive transport model RT3D in a watershed system. For aquifers with density-dependent flow (e.g., coastal aquifers) several coupled commercial models (e.g., FEFLOW, HydroGeoSphere, MIKE-SHE, etc.) are available. Coupled public domain models with density-dependent flow are relatively immature, which is particularly true for karst aquifers with conduit flow.

Participation is the second basic component of effective groundwater sustainability evaluation (Figure 2). This is particularly important because human behavior and societal preferences can be considered a root cause of unsustainability as well as part of the solution (Castilla-Rho et al., 2019; Elshall et al., 2021). For example, Castilla-Rho et al. (2017) examine human behavior, cooperation and collective action, and illustrate tipping points where social norms towards groundwater conservation shift abruptly with changes in cultural values. On the other hand, Shalsi et al. (2019) present an Australian case study in which co-management through local collective action was successful in recovering an aquifer that was at risk of depletion and subject to groundwater quality degradation including salinization. In addition, the authors suggest that co-management through local collective action can improve the social acceptability of new groundwater initiatives such as managed aquifer recharge and conjunctive use of surface water – groundwater (SW-GW).

Uncertainty analysis is the third component of effective groundwater sustainability evaluation (Figure.2). Uncertainty analysis is an integral part of groundwater sustainability policy through provisions such as the precautionary principle in the EU-WFD, and adaptive management in SGMA. In practice, decisions on groundwater sustainability in a changing environment are difficult because our scientific knowledge about complex groundwater systems is inherently uncertain, and because societal preferences are difficult to elicit and may be conflicting. This requires a broad uncertainty analysis accounting for natural and societal aspects (Elshall et al., 2021; Refsgaard et al., 2007).

There are eight essential factors to consider when evaluating groundwater sustainability at local, regional, and transboundary scales (Elshall et al., 2021, 2020; Pierce et al., 2013). Among the eight factors, five factors related to aquifer performance are (1) recharge rates and storage conditions, (2) water quality, (3) groundwater capture, discharge rates, and environmental flows, (4) natural hazards and threats, and (5) facilities and technologies of water resources management. Examples of natural hazards and threats are land subsidence due to over-pumping, sinkholes, and severe prolonged droughts. Examples of facilities and technologies are pumping and water distribution systems as well as managed aquifer recharge. Factors (1-4) are related to the physical aquifer system, and Factor (5) is related the infrastructure system. Three factors related to aquifer governance are (6) legal and institutional constraints, (7) societal values and preferences, and (8) economic feasibility. Societal values and preferences include instrumental, intrinsic, relational, and aesthetic values, intragenerational and intergenerational equity, public health, resilience, indigenous rights, and consensus as described by Elshall et al. (2020). Factor (6) is related to institutional system, and factors (7-8) are related to the socioeconomic system.

In this section we only provide a brief overview on the concept of groundwater sustainability, for detailed information about groundwater depletion, challenges, and sustainability the reader is referred to recent studies (Bierkens and Wada, 2019; Elshall et al., 2021, 2020; Gleeson et al., 2020; Lall et al., 2020; Rinaudo et al., 2020). Given this brief overview, effective application of such a participation-based and multi-process approach with broad uncertainty analysis remains problematic for both the academic community and water managers (Elshall et al., 2020; Thompson, Jr. et al., 2021). We then show how the current digital transformation can influence our groundwater sustainability practices.

3. Digital groundwater

Initiatives such as the INSPIRE Directive (https://inspire.ec.europa.eu) of the European Union (EU) Commission, and the EarthCube initiative for geosciences (https://www.earthcube.org) of the National Science Foundation (NSF) in the U.S. promote the increased use of information and communications technology (ICT) to build cyberinfrastructure for geosciences. This is mainly to assist in the creation, dissemination, and application of geoscientific data and research to the benefit of society. For example, to support sustainable development, the Infrastructure for Spatial Information in the European Community (INSPIRE) is a Directive to establish an EU spatial data infrastructure to support environmental policies and environmental applications. The EarthCube aims at transforming the conduct of geoscience research, education, and accordingly their services to the society, by encouraging the geoscience community to systematically build geoscience cyberinfrastructure through community dialogue, governance, and a common vision (NSF, 2015). Research agendas for intelligent systems and digital initiatives are emerging to serve this digital transformation (Chen et al., 2020; Gil et al., 2018; Hubbard et al., 2020). For example, the Digital Water Program (https://iwa-network.org/programs/digital-water) of the International Water Association (IWA) serves as a starting point to initiate the dialogue on digital water, and to share solutions and experiences in applying digital solutions for water utilities. In addition, strategy and recommendations for U.S. Executive Presidential Order 13956 (10/16/2020) —Modernizing America's Water Resource Management and Water Infrastructure — emphasize the importance of the next generation water observation networks and water resources modeling capability, leveraging on ICT (Petty et al., 2021).

An example of this digital transformation is smart groundwater management, which can improve groundwater sustainability practices. Many aspects of geoscience domains such as groundwater hydrology pose novel and challenging problems for intelligent systems research, which would significantly transform intelligent systems and greatly benefit the geosciences in turn (Gil et al., 2018). Intelligent/Smart systems are becoming more common, and they can be "intelligent/smart anything" such as smart agriculture, smart city, intelligent transportation system, smart home, and smart health care. For example, smart agriculture includes precise agriculture and smart irrigation (i.e., to estimate and supply the fertilizer and water needs at the resolution of individual plants), and smart greenhouse by controlling the physical environment to increase crop yield. Smart city includes intelligent transportation systems, smart grids, smart mobility, smart buildings, smart street lighting, online banking, telehealth, a digital twin of the city, and smart devices to allow citizens to connect to the smart city services. A digital twin of a city is a virtual representation of the systems of the city to enable stakeholders to monitor and manage water, air quality, energy, mobility, and other services in the city. While certain areas such as smart city and smart agriculture have reached a certain level of maturity, smart groundwater management is still evolving. Yet certain cross-disciplinary technologies and elements are shared among all these smart applications such as artificial intelligence, big data, blockchain technology, cloud computing, cyber-physical systems, digital twin, internet of things, and web-based platforms and workflows. For example, internet-of-things (IoT) is a deeply interconnected ecosystem of sensors, cameras, computers, smart systems, connected devices, smart devices, and other technologies to share data, work together to make decisions, and operate autonomously in the background. A web-based platform (a.k.a., science gateway, citizen science website, hub, e-Science, e-Research, virtual community platform, virtual research environment, virtual laboratory, etc.) combines a variety of cyberinfrastructure components (e.g., sensors, cloud computing, high performance computing, workflows, data repository, visualization tools, analysis tools, simulation tools, gaming tools, etc.) to support data collection and applications such that users can access diverse resources and communicate. A workflow (a.k.a., workflow software, scientific workflow system, workflow management system, workflow engine) is a software that manages processes and automates a process or more. Putting these pieces together to develop smart groundwater management applications is an emerging field. In this book chapter we provide a brief overview on emerging technologies, and discuss how these technologies can change our sustainable groundwater management practices.

4. IoT-based data collection

Advancement of sensor devices, and the inexpensive easy-to-use internet of things (IoT) -based technologies, leads to low-cost, low-power, open-source, and do-it-yourself (DIY) sensors and data logging solutions. Such high quality scientific measurements for environmental monitoring applications can be made using inexpensive and off-the-shelf components (Horsburgh et al., 2019). Examples of these sensor technologies and data logging solutions include microcontroller units such as the Arduino suite of products, single-board computers like the Raspberry Pi, and the diverse array of IoT devices (Horsburgh et al., 2019). These IoT-based low-cost and DIY sensing systems are gradually emerging. For example, the Openly Published Environmental Sensing project (https://open-sensing.org) at Oregon State University, which focuses on developing environmental sensing projects and research, offers tutorials for students and practitioners on DIY sensor networks. Currently in academic labs, an IoT-based borehole sensor, which measures water pressure and quality, can be an order of magnitude cheaper than a typical commercial senor. Examples of low-cost, community-based, and real-time groundwater monitoring networks with sensor-to-web data streaming are presented by Drage and Kennedy (2020) in Nova Scotia, Canada and by Calderwood et al. (2020) in California. Sensor data can be streamed to a web-based platform through Wi-Fi (Drage and Kennedy, 2020), cellular connection (Drage and Kennedy, 2020), and satellite (Thomas et al., 2019). Note that a *web-based platform* is generally accessed over a network connection, using a web browser or as a client-based desktop and mobile application, with most of the processing occurring on external servers.

The applications of the IoT-based sensors are diverse. These IoT-based, low-cost, and DIY sensing networks that stream data to a web-based platform can be particularly useful for developing countries (Maroli et al., 2021; Narendran et al., 2017). For example, Thomas et al. (2019) demonstrate that sensor network implementation across large spatial scales in arid regions in Africa can provide both practical benefits such as real-time monitoring of pump malfunction, and more importantly groundwater pumping data that are otherwise difficult to collect. For details about IoT-based monitoring networks and their related applications in smart water management, the reader is referred to recent review articles (Abdul Salam, 2020; Jan et al., 2021; Varadharajan et al., 2019). As these IoT based low-cost sensing systems are allowing easy collection of high-frequency data, this is accordingly changing our practices for data logging, transmission, storage, sharing, processing, and usage as discussed below.

5. Web-based data sharing

To improve groundwater spatial data infrastructure and to sustainably manage water resources, several data networks are already emerging in hydrology. *Spatial data infrastructure* (SDI), which consists of spatial data, metadata, models, tools, and interactive user interfaces, is a digital infrastructure that enables the sharing and flexible use of data. The internet of water for sharing and integrating water data is emerging through diverse water platforms that enable open water data, integrate existing public water data, and connect regional data sharing communities (Patterson et al., 2017). These water platforms are increasing in number not only in response to technological advances, societal needs, and initiatives such as EarthCube, but also due to policy changes. For example, the Subcommittee on Water Availability and Quality of the U.S. Office of Science and Technology Policy enacted the Open Water Data Initiative in 2014, which was chartered under the Department of the Interior's Advisory Committee on Water Information (http://acwi.gov/spatial/index.html) as an organized effort to provide water data, and community applications built on these data (Bales, 2016).

A water platform could be non-spatially bounded, forming around a unified purpose (Patterson et al., 2017). For example, HydroShare (https://www.hydroshare.org) of the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) is a water platform with generic data model and content packaging scheme to allow the hydrologic science community to store, manage, share, publish, annotate, and collaborate around diverse types of data and models (Horsburgh et al., 2016; Morsy et al., 2017). Another example is WHYMAP (https://www.whymap.org) – the World-wide Hydrogeological Mapping and Assessment Program, which among its main purposes are to summarize groundwater information on the global scale, provide a groundwater resources map of the world, and provide map information for international discussion on water. The Water Information Network System (WINS) of Intergovernmental Hydrological Program (IHP) of the UNESCO (https://en.unesco.org/ihp-wins) is an open access platform for sharing water-related information and connecting water stakeholders from developed and developing countries. The WaterShare (http://www.watershare.eu) is platform for global to local collaboration, and knowledge sharing of water solutions and innovations to contribute to achieving the SDG6. In addition to abovementioned discipline-specific repositories, there are general repositories for data sharing and collaboration. Stall et al. (2020) provide a comparison of general repositories such as the Open Science Framework (https://osf.io) for project management through the entire project life cycle based on open science best practices. The choice of the best repository for data sharing is case specific depending on the project size and features, funding agency requirements, community needs, and many other factors Generally, choosing a well-established and trustworthy hydrology-specific repository would support the hydrology community.

A web-based water platform could be spatially bounded for data and model sharing and community collaboration (Patterson et al., 2017). For example, the online groundwater database of the Texas Water Development Board is a spatially bounded groundwater platform that allows access to information about Texas aquifers (Rosen et al., 2019), following the FAIR data principles such that data are Findable, Accessible, Interoperable, and Reusable (Wilkinson et al., 2016). This platform allows users to access Texas groundwater data, understand the implications of contamination events, and determine long-term groundwater availability trends (Rosen et al., 2019). An example of a more generic regional platform that is also based on FAIR data principles is the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC, https://data.gulfresearchinitiative.org), which is a data management system for the full life cycle of data for researchers in the Gulf of Mexico. A spatially bounded groundwater platform is not necessarily regional, but can range from a local to transboundary scale data networks that supply heterogeneous data to users. For example, through conformance to international standards, SDI architectures, and shared vocabularies, the Canadian Groundwater Information Network (GIN) and the U.S. National Ground-Water Monitoring Network (NGWMN), are examples of large groundwater data networks that can be interoperable allowing public access to harmonized groundwater data from shared international borders (Brodaric et al., 2016). A web-based platform for groundwater data could be spatially bounded not only to share data and models, but also to serve as a platform for community collaboration as discussed below.

Web-based data sharing requires SDI and standards that shapes the data model. A *data model* determines the vocabulary and structure of how data is collected, stored, processed, queried, and visualized in a data network. *Interoperability* among data models permits a common language among data networks to make data quarriable and seamlessly usable across data networks regardless of its original heterogeneity. Accordingly, standardization across data models is needed. For example, GroundWaterML2 (GWML2, Brodaric et al., 2018) consists of data structures and encoding guidelines for hydrogeology web-data exchange. GWML2 is a new global standard for international groundwater data representation that is developed by the Groundwater Standards Working Group of the Open Geospatial Consortium (OGC). GroundWaterML2 is compliant with the concepts, standards and technologies of SDI, and can be used in conjunction with a variety of web services as central structure for the query and transport of data. This enables online data interoperability at multiple levels amongst numerous and heterogeneous data sources. Similarly, the EU-wide INSPIRE addresses 34 spatial data themes (e.g., INSPIRE-Meteorology, INSPIRE-Geology, INSPIRE-Landcover, INSPIRE-Landuse, INSPIRE-Hydrograph, etc.) that are relevant to the environment to ensures data accessibility and seamless data combination from different sources and across different scales and levels (Ilie and Gogu, 2019). The INSPIRE-Hydrogeology is part of the INSPIRE-Geology.

The hydrology community pursues achieving more compatibility among different data representations. This requires interoperability between their representations at the levels of syntactic, schematic and semantic that include the differences in terminology and definitions (Hahmann et al., 2016). For example, by describing how terms (e.g., geologic unit, or water body) are used in different data models, a conversion to and from GWML2 with INSPIRE-Hydrogeology is seamless. In addition, although a significant attention has been devoted to the sharing and reusing hydrological data than hydrological models, flexible and general metadata frameworks for model sharing are emerging across wide variety of models (Morsy et al., 2017). Finally, data configuration managers are needed for customizing data requirements. For example, Wang et al. (2020) propose a universal data exchange model that provides data to users through data services rather than through downloading raw data files. This data configuration manager additionally provides interactive programming tools for data customization, and a component-based data viewer of different types of hydrological information (Wang et al., 2020).

6. Workflow for data processing

The scope of the workflow depends on the level of vertical integration and horizontal scope as shown in Figure 3. For example, after manual or automatic data retrieval from sensors, data networks, collaborative data updates, and user data, the workflow for data processing can range from basic data analysis and visualization to model-based analysis and decision support. Dahlhaus et al. (2016) developed a groundwater web-based platform for the State of Victoria in Australia with tools for data querying and 3D visualizations. This includes simple data analysis such as the ability to query the predicted depth to water table, water quality and hydrostratigraphy at any selected point, and provides virtual borehole logs at any selected location in Victoria. A workflow with a wider data processing scope can include executing existing model instances or developing new model instances, given both phenomenological and process-based groundwater model programs. Note that a model program is a logical representation of ideas as source codes or compiled executables that can be used to execute many model instances with different input files, and generates output files. An example of a model program is MODFLOW, a widely used modular finite-difference flow model that solves the groundwater flow equation. An example of model instance is the MODFLOW input files representing the hydrological settings and conditions at a specific site and a given scenario. Automating the workflow for data processing requires an application programming interface (API) to communicate with the model in a batch mode that is without end user interaction. For example, the Python based FloPy facilitates interacting with MODFLOW to configure input files, execute model, and analyze model outputs (Bakker et al., 2021). Similarly, PhreeqPy provides Python tools to work with PHREEQC for reactive transport modeling (Charlton and Parkhurst, 2011).

Additionally, several tools are available interface among different models and components in a batch mode. For example, the Open Modeling Interface Standard (OpenMI) defines an interface that allows models to run simultaneously and exchange data in memory at run-time (e.g., at each time step) making model integration feasible (Becker and Burzel, 2016; Gregersen et al., 2007). Upton et al. (2020) use OpenMI to develop a multi-scale groundwater modeling method to evaluate groundwater sustainability. Coupling and interfaces tools integrated water resources modeling is an active research area. Malard et al. (2017) developed a tool for dynamic coupling of system dynamics and physically-based models that makes coupled models much more reproducible and accessible to stakeholders. Note that system dynamics is an approach to understand the interactions, behavior, and feedback loops of constituent components of a system. For detail about model linking, integrated modeling, and interface standard, Zhang et al. (2021) discuss sharing, reusing, and interoperation of models across different standards (e.g., OpenMI, BMI, and OpenGMS-IS).

Workflows with larger scopes are emerging. The scope of the workflow for data processing can expand horizontally by including more advanced levels of groundwater modeling such as integrated modeling and digital twin, or by supporting more data usage applications (Figure 3). The scope of the workflow for data processing component can expand vertically with forward and backward integration with other components (e.g., data collection, data sharing, data reporting, etc.). For example, De Filippis et al. (2020) used commonly available standards and tools to develop a workflow to collect and process vadose-zone data from field sensors to simulate percolation to the water table with automatic generation of summary reports like plots and tables. Barnhart et al. (2010) develop a data assimilation method that integrates groundwater contaminant transport models with wireless sensor networks. Su et al., (2020) propose a similar a web-based workflow for groundwater simulation. In addition, a workflow can link the groundwater models to model-development and decision-support tools for parameter estimation, data assimilation, surrogate modeling, sensitivity analysis, simulation optimization, agent-base modeling, and uncertainty quantification. These tools are generally based on optimization algorithms, sampling algorithms, and machine and deep learning algorithms.

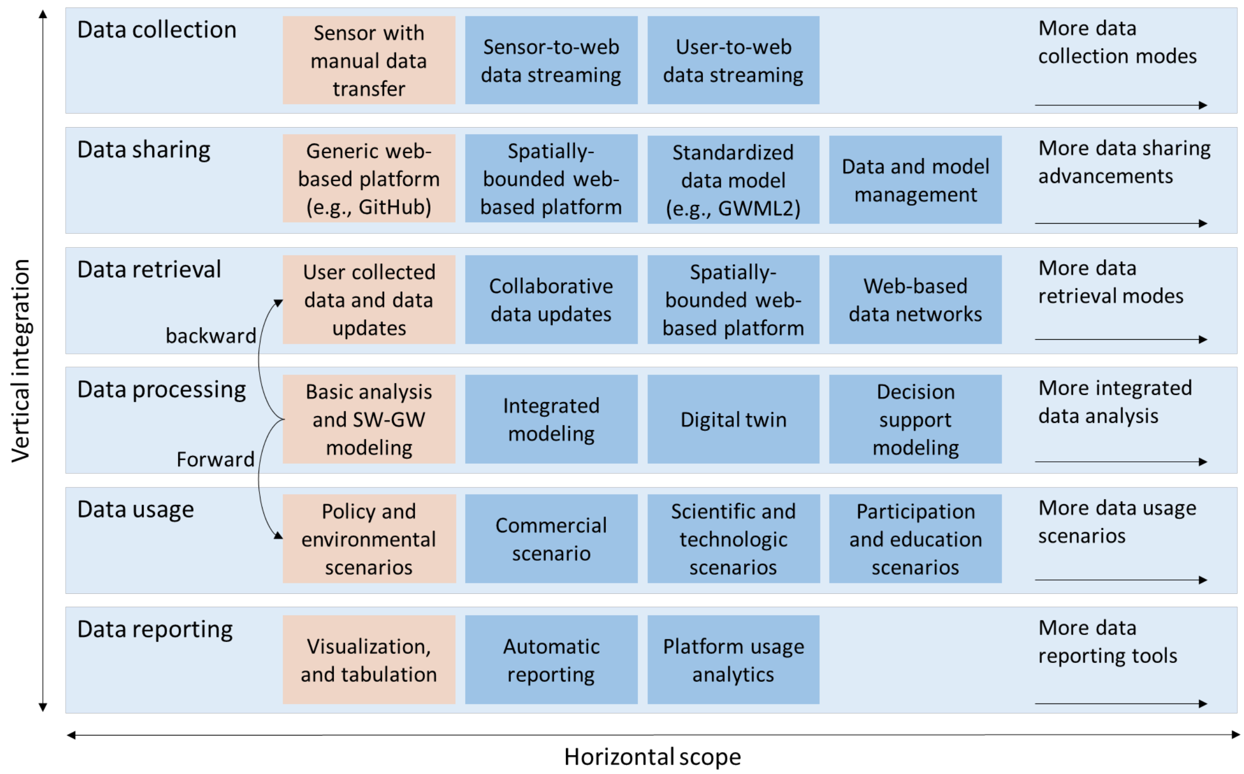


Figure 3. Different components of the workflow. The workflow can expand through forward and backward vertical integration of different components (y-axis), and through expanding the scope of each component by considering further subcomponents and advancements (x-axis). Blocks highlighted in orange represent an example of a basic workflow where the data is manually collected and stored on a generic web-based platform for data sharing, and then the workflow retrieves the user data, update and run a SW-GW model, analyze the model outputs with respect to a policy problem, and reports figures and tables.

Diverse workflows have been developed to process data for analyzing surface water-groundwater (SW-GW) resources. Workflows with IoT-based data acquisition and wide scope of data processing is nascent in groundwater hydrology relative to surface water hydrology. Examples of simple to more involved workflows in surface water hydrology are numerous. For example, to solve the lack of transparency on model creation, Chawanda et al. (2020) developed the workflow software (SWAT+AW), which is an automatic workflow (AW) that automates the creation of catchment hydrological model instances for the Soil and Water Assessment Tool (SWAT) model program using user collected data. To increase the SWAT model usage for non-technically trained stakeholders and decision makers, McDonald et al. (2019) developed a web-based SWATOnline workflow with modular web applications such as automatic climate data retrieval from the National Aeronautics and Space Administration (NASA) servers. Hou et al. (2019) review the input data preparation methods from manual data preparation to intelligent geoprocessing, which allows full automated data preparation for geospatial modeling and is adaptive to application contexts. An emerging trend is to move toward more vertical integration and horizontal advances and expansion (Figure 3). For example, Taylor et al. (2021) developed a web-based platform with cloud computing that standardizes the user workflow and pre-integrates models and data. This allows users such as water planners and educators to rapidly develop case studies for basin-scale water assessment and scenario investigation to assess changes arising from developments in agriculture, water storages, population growth, and climate changes.

In groundwater hydrology, more integrated workflows are also developing. For example, FREEWAT (Rossetto et al., 2018), which is funded by the EU Commission, integrates open source models and tools for SW-GW management supporting data collection, data sharing, and data analysis for supporting model-based planning and decision-making. FREEWAT uses the FloPy Python library to connect SW-GW models with a toolbox for model calibration and uncertain quantification in a QGIS-enabled and integrated environment for spatial data management, processing, and visualization. QGIS is an open-source cross-platform geographic information system software. The FREEWAT supported a number of models, including the integrated SW-GW MF-OWHM, a Crop Growth Module for crop yield modeling, MT3D-USGS and MT3DMS for solute transport in the unsaturated and saturated zones, and SEAWAT for density-dependent groundwater flow. De Filippis et al. (2020a) displays a total of 13 case studies in European and non-European countries where the FREEWAT platform along with information and communication technologies were applied for SW-GW management, transboundary aquifer management, protection of groundwater-dependent ecosystems, and rural water management. The case studies show that improved access to data and the portability of models and model results can help promote water sustainability from the local to basin scales.

In addition to data analysis with respect to SW-GW resources, workflows are emerging to address the other components of groundwater sustainability evaluation (Figure 2) that are groundwater-dependent ecosystems, human activities, uncertainty analysis, and participation. Workflows for the protection of groundwater-dependent ecosystems are emerging (Tague and Frew, 2021; Turner et al., 2020; Wohner et al., 2020). Workflows generally accounts for human activities using simple techniques such as scenario analysis. For example, Bojovic et al. (2018) developed a web-based platform to facilitate stakeholder collaboration in the analysis of water management adaptation options in the Alps. As integrating social and hydrologic data in an elaborate socio-hydrology analysis can be generally challenging, Flint et al. (2017) provide social water science data classification and recommendations on data management considerations for cyberinfrastructure purposes. With respect to uncertainty analysis, White et al. (2020) provide a MODFLOW-based groundwater modeling framework that uses FloPy to develop a workflow for parameter estimation and uncertainty quantification. With respect to participation, several levels and forms of participation exist such as collaborative modeling with key stakeholders, general public participation for planning and decision-making, peering for scientific research, commons-based peer management including co-design and co-decision making, among many other forms. Examples of mature workflows and platforms for spatially bounded and community centered collaboration include the Bay Delta Live for the San Francisco Bay-Delta estuary in California (https://www.baydeltalive.com) for water and ecosystem services management. Bay Delta Live, in which Southern California's Metropolitan Water District invested two million dollars over five years to help launch the platform, includes modules for collaboration with a desktop and phone applications providing real-time information for daily decision-making (Jooste, 2017).

7. Scenarios for data usage

Web-based platforms for groundwater sustainability can support a number of application scenarios. For example, Brodaric et al. (2018) identify five data usage scenarios that motivate GWML2, which are commercial scenario, policy scenario, environmental scenario, scientific scenario, and technologic scenario. The policy scenario includes administrative reporting on withdrawal limits, sharing information across different water authorities, and incentive mechanisms for groundwater policy implementation. For example, in response to SGMA, which mandates the creation of local groups to develop and implement solutions to make their local groundwater usage sustainable by 2040, a pilot project in Sacramento-San Joaquin River Delta, California is developing a low-cost satellite connected sensors with real-time groundwater data streaming to IBM Blockchain Platform (IBM Research, 2019). The environmental scenario includes components such as monitoring, protection and management groundwater-dependent ecosystems. For example, the Bay Delta Live web-based platform focuses on understanding the complex and dynamic ecosystem of the Sacramento-San Joaquin Bay Delta (Patterson et al., 2017).

An example of the commercial scenario is to estimate the cost and timeline for drilling a new well. A well driller can use a web platform to explore the local geology, and inspects wells located near the target area in terms of the lithology, water level, yield, and total depth at each well (Brodaric et al., 2018).

Scientific scenario includes data sharing, data usage, and peering to perform multiple scientific activities such as data analysis, model development, data worth analysis, and model-based analysis. For example, the HydroShare of CUAHSI was mainly developed to facilitate data and model sharing in the academic community. A spatially bounded example is a web-based workflow developed by Shuler and Mariner (2020) for collaborative groundwater modeling with key stakeholders at the American Samoa. Bandaragoda et al. (2019) discuss how the existing cyberinfrastructure tools and resources can enable collaborative numerical modeling in Earth sciences. Additionally, this can serve as a platform for peering within the scientific community and with stakeholders, and broadens the use of scientific applications such as integrated-model simulation and gaming to stakeholders. Moreover, these web-based platforms with monitoring data can support machine learning-based data exploration (Rau et al., 2020), and groundwater representation in continental to global scale models(Gleeson et al., 2021).

The technologic scenario involves data delivery situations, which require compatibility with other hydrogeological data representations to enable data interoperability within a groundwater data network, and between different data networks (Brodaric et al., 2018). In addition, this includes communication with other devices to create a cyber-physical system (CPS), in which a process is monitored and controlled through the IoT. For example, Wang et al. (2013) present a case study in Xiamen City, China, in which an IoT-based online water quality management system maintains water level of the Scenic river by automatically supplementing reclaimed domestic wastewater and fresh surface water from the Xinglin Bay, and cycling landscape water to stabilize the water quality. CPS is a widely used technology in smart water applications to manage water supply networks (Kulkarni and Farnham, 2016; Pan et al., 2015).

Other data usage scenarios are participation and education. Web-based groundwater platforms allow open community participation from different physical locations and domains of expertise to join the groundwater exploration, to easily exchange idea with less thresholds as compared to centralized systems, and to perform comprehensive modelling and analysis tasks collaboratively (Chen et al., 2020). For example, to help communicate complex hydrogeological concepts to improve confidence in decision-making, Wolhuter et al., (2020) developed the 3D Water Atlas of the Surat Basin, Queensland, Australia. This is an interactive web-based platform based on a three-dimensional geological model for visualizing and analyzing hydraulic and hydrogeochemical data from boreholes in a way that is accessible to a wide audience. Dahlhaus et al. (2016) show that the web-based groundwater platform of the State of Victoria, which was developed outside of the government to meet end-user needs and to educate a broader community, has increased the end user interaction and participation, empowering society with the value of big data to guide future planning for sustainable and equitable groundwater.

Education is a valuable data usage scenario. Bridging sustainability science, Earth science, and data science requires interdisciplinary education with competencies in data processing and model development (Pennington et al., 2020). To prepare future hydrologists and engineers, Lane et al. (2021) present HydroLearn, an open web-based educational platform to provide a formal pedagogical structure for developing effective problem-based learning activities. Targeting upper-level undergraduate and early graduate students in hydrology and engineering, HydroLearn allows the students to explore how well models or equations work in particular settings or to answer specific problems using real data (Lane et al., 2021).

8. Perspectives of web-based groundwater platforms

The advances in technology are enabling the transition toward smart groundwater management, and accordingly the increase in the number and scope of web-based groundwater platforms. This will change the paradigm for managing groundwater as these web-based groundwater platforms enable open resource and data sharing, open integrated modelling and simulation to be performed, and open community to grow and expand organically (Chen et al., 2020). Given the technologies of the fourth industrial revolution, we discuss a spatially bounded, web-based groundwater platform with a digital twin for commons-peer management of groundwater resources. We also discuss how these platforms can improve groundwater sustainability practices.

The web-based groundwater platform connects the workflow with available computing resources, and provides a web-based interface for users. As many of the workflows require extensive processing power, storage space, and communication speed, they are executed over a largescale platform with user interfaces. Users include expert users, who have certain technical and scientific knowledge about parts of the topic, and general stakeholders, who might know less about the topic from a technical perspective though they could have ample indigenous and intuitive knowledge about the topic (Chen et al., 2020). A web-based platform has several advantages such that the platform users do not need to install software and manage updates, the platform connects to cloud-based high performing computing resources, and the platform automatically retrieves data from data networks. Currently, cyberinfrastructure is reaching a point where it is possible to build open and transparent environmental modeling systems (Choi et al., 2021). As such, computational environments are interlinked with sensors and data repositories, supported by APIs for programmatic control of the modeling activities and the workflow, serve as gateways to high performance computing resources, and provide user web-based interfaces (Chen et al., 2020; Choi et al., 2021; Hubbard et al., 2020).

A spatially bounded web-based groundwater platform can mature to a digital-twin for commons-based peer management of groundwater resources. Groundwater workflows are developing to allow for more advanced data processing. Goodall et al. (2011) discuss modeling water resource systems using a service-oriented computing paradigm, which is software engineering paradigm that deals with a complex software system as an interconnected collection of distributed computational components. An advanced web-based workflow such as the one shown in Figure 4 is nascent in groundwater hydrology. The workflow shown in Figure 4 allows for data search, collection, and harmonization from data networks and sensor-to-web data streaming, data and model representation following international standards (e.g., OGC standards), and model programs and instances linkage with decision-support tools. One of the existing workflows that includes several of the components shown in Figure 4 is FREEWAT, which can be used and extended for smart groundwater management especially in regions with historical water scarcity exacerbated by climate change (Theuma et al., 2017). Other existing tools include Delft-FEWS (https://oss.deltares.nl/web/delft-fews) that is an open platform that integrates data and models. For example, van der Vat et al. (2019) use Delft-FEWS to develop the Ganga Water Information System(GangaWIS) that contains model inputs and relevant outputs of SW-GW models that support strategic planning in the Ganga Basin in India.

The workflow scope can be expanded to include a digital twin, which is a virtual presentation of the aquifer system to enable stakeholders to monitor and manage the SW-GW system, groundwater-dependent ecosystems, and groundwater-dependent human activities (e.g., irrigation, municipal water supply, etc.). A digital twin of the aquifer changes as the physical aquifer changes. For example, sensor-to-web data streaming and data assimilation techniques update the groundwater flow model, water budget calculation, solute transport model, groundwater dependent ecosystem indicators, and groundwater sustainability indicators. The digital twin can expand in scope to serve as an integrated groundwater system in the digital world, which changes as its natural and social counterparts change. This can be particularly useful in an agricultural setting where this groundwater digital twin works together with a smart agriculture system.

The web-based groundwater platform has a web-based interface for applications. This web-based interface will typically include a web-stie for static information such site-specific documents and tutorials, data viewer to present data from the database, and dashboard with different options related to data viewing, processing, and post-analysis. The web-based platform can be accessed through a web browser, and as a client-based desktop and mobile application as needed.

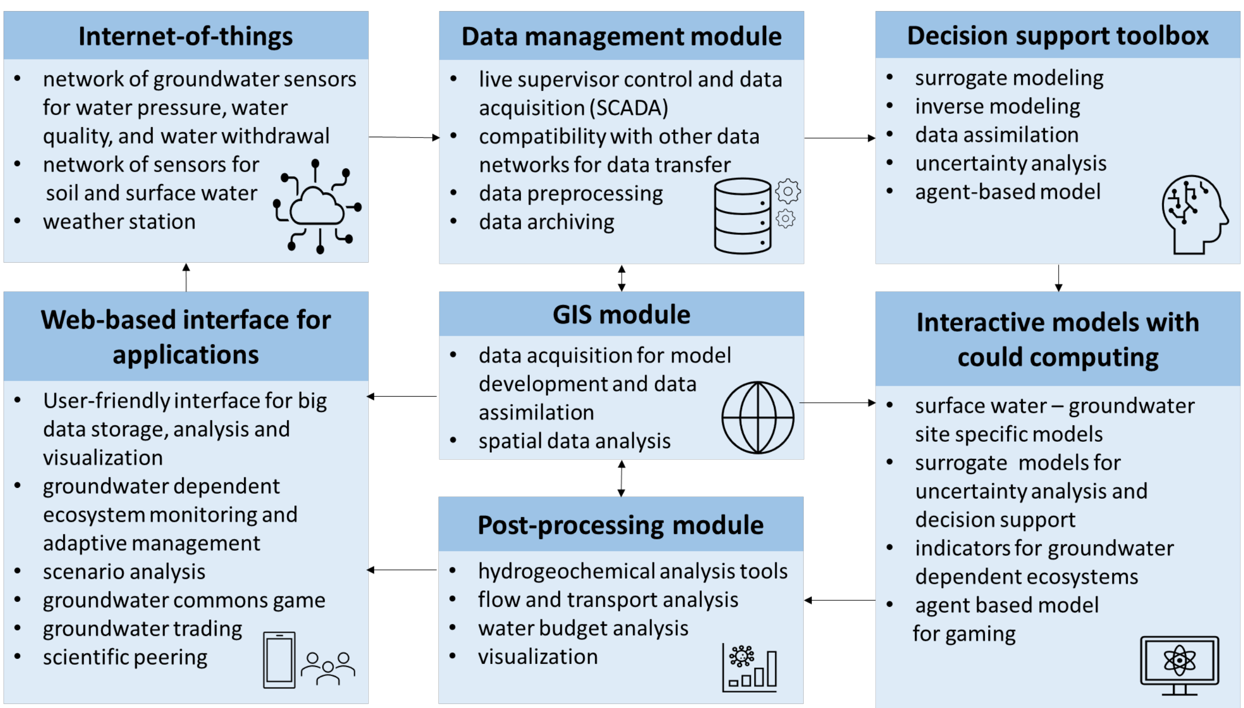


Figure 4. Components of a web-based groundwater platform with a digital twin for commons-based peer management of groundwater resources.

A spatially bounded, web-based groundwater platform can extend beyond merely sharing data, models, and computational resources, to provide multiple water resources and environmental management services. "In the future, your performance metric will not be how many people visit your website, but how many applications your data support" (ClimateWire, 2015 as cited in Bales, 2016). Section 7 presents several data-usage scenarios, and here we expand on the participation and education data-usage scenarios. Participation and education are particularly important for groundwater sustainability as human behavior is a root cause of unsustainability, but also part of the solution (Castilla-Rho et al., 2019; Elshall et al., 2021). Creating a digital representation of the groundwater system provides a platform to create a conversation. Providing analysis and digital management tools can create a space for creativity, build trust, and facilitate commons-peer management of groundwater resources. This includes tools for integrated simulation tasks for expert and non-expert users with scenario analysis and gaming. Such applications can shift user perspectives by learning about thresholds, tipping-points, and pathways of the coupled water-human system. Digital management tools include blockchain-based smart contracts and groundwater credits. For example, IBM Blockchain Platform has a web-based dashboard for groundwater users, financers, and regulators to real-time monitor and track groundwater data and user transactions including features such as smart contracts in which transactions are automatically executed when the conditions are matched (IBM Research, 2019). This platform supports policy and market mechanisms such as groundwater individual users share cap, groundwater credit, groundwater share purchase, and groundwater trading. Thus, these web-based platforms facilities not only the co-production of data (e.g., hydraulic and geochemical data), information (e.g., water budget), and knowledge (e.g., sustainable pumping limits), but also co-decision making and joint action with respect to groundwater pumping and groundwater trading.

The advancements of these web-based groundwater platforms can eventually lead to commons-peer management of groundwater resources. The term *commons-based peer production* was coined by Benkler (2002) to refer to a social-economic phenomenon emerging in which a large number of people work cooperatively without the traditional firm-based or market-based ownership of the resulting product. Examples include working on large and small-scale projects, generally, online (e.g., Wikipedia, Python, Linux, open source software, etc.), but sometimes offline (e.g., community gardening). To produce data, knowledge, and goods, commons-based peer production follows motivational drives and social signals, rather than market prices and managerial commands (Benkler, 2002; Benkler and Nissenbaum, 2006). Accordingly, commons-based peer production can be regarded as a virtuous behavior, and a society that provides opportunities for virtuous behavior is one that is more conducive to virtuous individuals (Benkler and Nissenbaum, 2006). This is particularly important because among the reasons of groundwater unsustainability are the influence of some social groups over less privileged social groups in water resources governance (Baldassarre et al., 2021; Méndez-Barrientos et al., 2020), and when individual profits prevail over the need to preserve a common resource (Leduc et al., 2017). Thus, commons-based peer management improves equity and inclusivity, and can be regarded as a form of managing the groundwater as a common-pool resource (Ostrom, 1990). A common-pool resource (e.g., groundwater, fishpond, etc.) is an economic term referring to a resource that is shared and available to everyone like public goods, but with variable and limited stock that is subject to rivalrous consumption like private goods such that each unit consumption subtracts from the total stock(Hayes, 2021). The common-pool resource is subject to the tragedy of the commons(Hardin, 1968) that is when individuals try to maximize their self-interest regardless of the social cost. Unlike public goods that can be utilized without reducing availability for others, a common-pool resource requires protection to prevent overuse and congestion, and to ensure continuous and nonexcludable supply. While this generally calls for government regulation, it additionally calls for commos-based peer management.

Disclaimer

The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

Acknowledgements

The first two authors of the book chapter were supported by the NSF Award #1939994, and NSF grant EAR-1552329.

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