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A Snapshot of the World's Groundwater Challenges

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Abstract

Depletion and pollution of groundwater, Earth's largest and most accessible freshwater stock, is a global sustainability concern. A changing climate, marked by more frequent and intense hydrologic extremes, poses threats to groundwater recharge and amplifies groundwater use. However, widespread human development and contamination of groundwater reservoirs pose an immediate threat of resource extinction with impacts in many regions with dense population or intensive agriculture. A rapid increase in global groundwater studies has emerged, but this has also highlighted the extreme paucity of data for substantive trend analyses and assessment of the state of the global resource. Noting the difficulty in seeing and measuring this typically invisible resource, we discuss factors that determine the current state of global groundwater, including the uncertainties accompanying data and modeling, with an eye to identifying emerging issues and the prospects for informing local to global resource management in critical regions. We comment on some prospective management strategies.

Contents

1. INTRODUCTION

Groundwater accounts for 99% of the liquid freshwater stock on Earth and is the world's most accessed freshwater reservoir. In many regions, groundwater may be the only perennial water source, and it typically becomes the primary source where energy and equipment are available for pumping. It is also important as a buffer to seasonal and longer-term variations in surface water availability due to climate variability. Groundwater now accounts for almost half of all drinking water, approximately 40% of irrigation water, and a third of the water for industry (1).

Increasing withdrawals to meet growing human needs have led to significant groundwater depletion in major agricultural and population centers. Many aquifers may be threatened with extinction or are now seasonally exhausted. The expansion of intensive agriculture and associated irrigation is a primary driver. Urban and rural domestic groundwater consumption has also seen a dramatic increase. Deeper, confined aquifers can be relatively unaffected by biological and chemical contamination, and hence are prime targets for domestic water supply, especially where geogenic contamination (e.g., arsenic) is not an issue.

Contamination of near surface and subsurface water sources has become endemic as human activities intersect with water flow pathways. Fertilizers and pesticides used in agriculture, solvents, chemicals used in manufacturing, mining, energy production and commercial applications, and pharmaceuticals and pathogens introduced through human waste, are leading to chronic contamination of shallow and deep groundwater worldwide.

Given their long residence times, groundwater reflects the cumulative effects of extraction, recharge, and contamination. The resulting water depletion, pollution, and land subsidence may become irreversible due to the prohibitive cost of remediation. The degradation of groundwater quality due to a combination of geogenic and anthropogenic factors and large-scale depletion pose a sustainability challenge for humanity.

Sustainability: ability to maintain an activity without adverse impacts

Climate change: long-term variations in climate due to human or natural causes

However, groundwater problems are typically highlighted as a concern in only specific locations (e.g., Mexico City, North China, North India, Pakistan, California). By contrast, anthropogenic climate change is seen as a pervasive global concern that emerges such that carbon emissions at any location impact the global outcome. Extinction of local groundwater sources can have broad impact through agricultural value chains and could stimulate mass migrations and economic failure in the same way that climate change may. Anthropogenic climate change may amplify this situation through increasing aridity in some regions, but the threat to groundwater from endogenous, regional human activity remains a primary challenge.

Modeling: the use of conceptual, mathematical, or statistical techniques to analyze a system

Monitoring and understanding the coupled human and natural dynamics (e.g., physics, biology, chemistry, sociology and economics) of groundwater systems in response to climate variations and regional human activity is essential for developing appropriate management strategies and predicting social outcomes. There have been significant advances in hydrogeology, geophysics, geostatistics, and remote sensing and applied research in some of the more groundwater-stressed locations. Similar advances in social science literature have documented the role of different instruments (e.g., allocation, regulation, enforcement, pricing, and markets). Yet, in many cases, at the space and time scales of management interest, groundwater remains invisible. Aquifers, groundwater users, and sources of contamination are heterogeneous. Data on water use and pollution at the appropriate spatial and temporal resolution to attribute changes to human and natural forcing are difficult to obtain. This common pool resource problem is consequently difficult to predict and manage. In subsequent sections, we synthesize (*a*) groundwater quantity and quality conditions and key challenges, (*b*) data limitations and the application of global groundwater models, (*c*) characteristics of groundwater management and examples of promising strategies, (*d*) and critical future issues.

2. STATE OF THE GROUNDWATER RESOURCE

Over the past few decades, growing interest in monitoring and managing groundwater has led to advances in research, technologies, policies, and practices for an improved understanding of subsurface water dynamics and its links to climate dynamics and human activity. At a planetary scale, remote sensing has enabled a mapping of large-scale changes in groundwater storage. The GRACE satellites have shown that 21 of the 37 main aquifers on Earth are being depleted (2). On a local scale, sensors are now cheaper, easier to deploy, and connected to the Internet to facilitate data aggregation and interpretation. Geophysical instrumentation and techniques provide new measurements leading to a better understanding of the subsurface properties. In this section, we present a synthesis of key issues of Groundwater Quantity and Quality and discuss the nature of the drivers (e.g., demographics, economics, climate) on groundwater conditions (**Figure 1**).

2.1. Groundwater Quantity

Groundwater can be found in layered sedimentary aquifers, in hard rock aquifers with complex inter-connections, and in Karst aquifers with large inter-connected solution cavities. A general mapping of the presence of each type of aquifer around the world, and estimates of groundwater stocks, is available from the World-Wide Hydrogeological Mapping and Assessment Programme (WHYMAP; **https://www.whymap.org/**). The International Groundwater Resource Assessment Center (IGRAC; **https://www.un-igrac.org/**) provides a platform for global information on groundwater data, issues, modeling, and management information. Depending on the location and the type of aquifer, a groundwater system can range from 10 to 10^5 km^2 in size. Irrigation accounts for an estimated 70% or more of the average withdrawals and is often manifest through a large and increasing number of wells (e.g., millions of new wells added per year in India) whose pumping is not explicitly measured or reported. Typically, water and energy balance models are used for a global assessment; these models require significant assumptions as to water use and use proxies for the key biophysical parameters that are inferred from satellite data or from other sources.

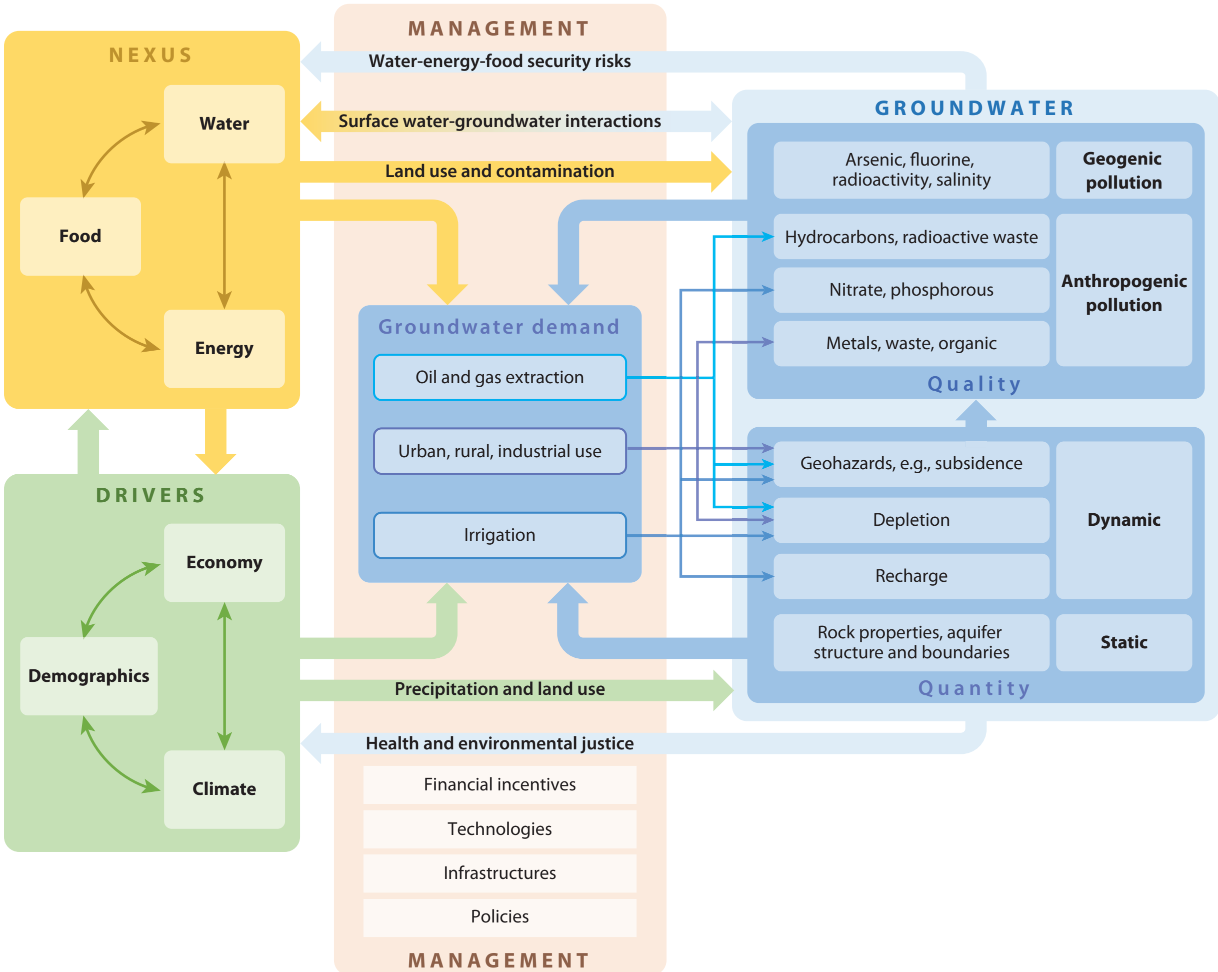

Figure 1

The characterization of groundwater resources requires a detailed comprehension of the static (e.g., geologic properties) and dynamic (e.g., water fluxes) parameters to describe groundwater quantity, and the pollutants to describe the groundwater quality. The state of the groundwater resources (*right column*) is determined by forcings such as demographics, land use and land cover change, economics, climate variability and trends, irrigated agriculture, and access to energy (*left column*). Groundwater use can lead to aquifer depletion, land subsidence, and contamination of aquifers. Groundwater management mitigates, amplifies, or regulates the impacts of the overarching forcings on the groundwater resources, through subsidies and financial incentives, new technologies, infrastructure provisions, or policies and regulations. Abbreviations: GW, groundwater; SW, surface water; WEF, water-energy-food.

In the absence of global (or even regional) data on deep aquifers, much of the global groundwater assessment modeling has focused on shallow aquifers, agriculture, and climate dynamics. However, most municipal and large-scale agricultural or industrial groundwater extraction points lie in deep aquifer layers. Deeper wells may be less susceptible to climate-driven changes in recharge, making the water sources more reliable. They may also be less susceptible to contamination. The deeper aquifers have been depleting across the world, with the trend accelerating in the twenty-first century because extraction rates often outpace recharge rates, and residence times are over a hundred years (3). The impacts of human use can manifest quickly (as in the hard rock aquifers of peninsular India that are emptied seasonally) or over decades (as seen in the progressive depletion of the sedimentary aquifers in North India, California, and the Midwestern United States).

High rates of extraction around major cities in the Americas, Asia, Europe, and the Middle East have led to localized depletion that in many cases (e.g., Bangkok, Beijing, Mexico City, Tokyo, Jakarta, Ho Chi Minh City, Dhaka, Osaka, Manila, Houston, San Jose, Shanghai, Venice, Kolkata, Madrid, and Granada) has translated into land subsidence (4–8). In these environments, groundwater depletion is due to high pumping rates and also to the reduction of recharge as the impervious cover in the area increases. As urbanization continues, especially in coastal cities and cities in deltas, we expect the trend of metro area groundwater depletion and land subsidence to continue with potentially higher susceptibility to flooding and groundwater salinization.

Irrigated agriculture, especially in arid regions, where solar radiation and soil health are not limiting factors, translates into a significant improvement in crop yields. Consequently, it is not surprising that governments, corporations, and farmers have adopted groundwater-based irrigation, with and without subsidies. More than 40% of irrigation water consumption comes from groundwater. India, China, and the United States have the most land equipped for irrigation using groundwater (9). India, China, North Africa, the Middle East, Central Asia, North America, and Australia are typically identified as places with large areas of groundwater depletion from fossil aquifers (10). Several authors (11–13) have tried to estimate the spatially distributed rates of groundwater depletion using satellite-derived gravity data (GRACE; see Section 3.1) and water balance models.

Climate variability plays a significant role in the variations in groundwater storage. For shallow aquifers variations in recharge due to persistent drought or wet periods have a direct effect on the water balance that is mediated by the degree and nature of exchanges between surface water and shallow groundwater, and by vegetation dynamics. For deeper aquifers, complex recharge routes and intermediate impermeable layers dampen climate-induced recharge variability.

Statistical investigations of linkages between climate variability and change and teleconnections with indices of interannual and decadal climate variability have been pursued in many places (14–19). Although the studies showcase significant interannual to multidecadal correlations, all highlight the difficulties in understanding the recharge mechanism and the consequent damping of the climate signal.

The relationship between climate and groundwater is made more complex by the impact climate has on pumping. Drought induces higher demand while simultaneously reducing renewable surface water, resulting in an increase in groundwater withdrawals and depletion. Correspondingly wet periods are accompanied by reduced pumping. The combined effect is an asymmetric amplification of the climate signal by the regional human response. Surface-groundwater interactions provide feedback loops (19–25) that can further amplify both surface and groundwater variations (see the sidebar titled Groundwater and Climate Change).

2.2. Groundwater Quality

The chemical, physical (e.g., turbidity), and biological quality of groundwater varies by location and depth. The presence of water contaminants may be controlled by geogenic factors, e.g., adsorption/desorption kinetics associated with soil/rock minerals, or anthropogenic factors, e.g., agrochemicals from farms or heavy metals from industrial processes; or a combination thereof, e.g., acid mine drainage from mining that mobilizes geogenic contaminants.

Processes that determine groundwater quality can be complex given that they reflect biogeochemical interactions at scales that are not readily observed. Characterizing the exact mechanisms requires an understanding of the pathways of water transport over a region. Water quality

GROUNDWATER AND CLIMATE CHANGE

Climate change is an amplifying stress factor for areas already experiencing groundwater depletion or pollution, implying significant changes in agricultural choices, urban water use efficiency, and water management (26–30). Recharge is difficult to quantify for past, current, and future climate (27). If rainfall intermittency and intensity increase, groundwater recharge rates may decrease. Changes in the spatial variability of vegetation and soils may modify recharge especially in arid regions. Groundwater depletion may lead to regional increases in induced recharge (20), confounding predictions of future recharge. Greenhouse gas emissions associated to groundwater stem from (*a*) the use of fossil fuels for the energy used in pumping (31–34), (*b*) bicarbonate or dissolved methane extraction (31, 35), and (*c*) changes in wetlands and riparian buffers (36, 37). Mishra et al. (31) estimate the CO_2 contribution from groundwater pumping in India to be approximately 5% of total Indian emissions. Wood & Hyndman (34) estimate the contribution for the United States is 1.7 million metric tons, which is insignificant compared to that from fossil fuel combustion. Groundwater extraction is not a significant direct contributor to climate change.

will change as groundwater travels through pore spaces with complex mechanisms of connectivity and exposure to chemicals and microbes embedded on aquifer material surfaces. Point measurements of groundwater quality are typically integrated with additional data sets, including lithology and land use, to map areas of concern and identify the sources. The IGRAC (**https://www.un-igrac.org/**) platform includes global maps of salinity, arsenic, and fluoride, which indicate high-risk areas. Regional- to country-level studies have been conducted for additional analytes.

There is a large literature on geogenic groundwater contamination by arsenic and fluoride, their mobilization, human exposure, and methods for treatment (38–47). While the quantitative assessment of groundwater quantity variations is highly uncertain, a global assessment of groundwater quality is not feasible (48). References 38, 39, 48–53 report on attempts to map or predict the locations of potential locations where geogenic contaminants may be a problem based on known lithology and limited measurements.

At the regional scale, arsenic and fluoride are major concerns in Asia, where groundwater is often the primary drinking water source. Countries with predicted and reported arsenic contamination exceeding 10% of their land area include Bangladesh, Cambodia, and Vietnam (39). In mainland China, 20 of 34 provinces have high arsenic concentrations in groundwater, potentially exposing more than 19 million people (47). Arsenic-related issues continue to emerge in many places and are endemic in the Indo-Gangetic plains, in parts of China, the United States, Western Africa, and South America. On the basis of soil, lithology, climate, land use, and elevation, arsenic contamination is predicted but is not yet confirmed by measurements in several Eastern European countries, Russia, and the Democratic Republic of the Congo (39).

Anthropogenic contamination of groundwater has emerged as a significant concern in the past several decades. Contaminant sources include agriculture (e.g., fertilizer, pesticides, hormones, antibiotics, and steroids consumed by livestock), urban (e.g., treated and untreated wastewater, septic systems, and other land treatment of solid and liquid wastes, golf course, and lawn applications), commercial/industrial (e.g., volatile hydrocarbons, wide range of chemicals that may be improperly discharged or injected into groundwater), energy (e.g., byproducts of oil and gas extraction, including from hydraulic fracturing, mobilization of natural methane, uranium, leaking storage tanks for fuels), and mining (e.g., chemicals used in ore processing, acids leaching from tailing ponds, heavy metals attached to sediments). Nitrates from agriculture, urban wastewater, and other sources are perhaps the most prevalent globally and have seen considerable attention as to their mobilization and control (54–61). The groundwater system functions as a receptor, a reactor, and an accumulator. Given the long residence times of groundwater, and the potential for biogeochemical activity that could create novel byproducts of the original pollutants, remediation or treatment of groundwater systems can be quite challenging.

Pharmaceuticals and personal care products fall into the class of Emerging Contaminants and are a growing concern, given that they pass through wastewater treatment plants and potentially through urban landfills (48, 62–67). Another class of man-made contaminants that are of significant recent concern are per- and polyfluoroalkyl substances (PFAS) (68). As with other sources of groundwater contamination, information on the prevalence and impact of these chemicals is poor (69) even where some regional studies have been performed (70). The National Groundwater Association provides an overview of the groundwater concerns with PFAS (71).

A special case of groundwater contamination relates to Karst aquifers (72–75). These aquifers exist around the world including where there has been dissolution of subsurface limestone leading to sinkholes and caves such that large amounts of water can be stored and conveyed. Karst aquifers cover approximately 15% of the ice-free land area of the world, may supply approximately 10% (72) to 25% (73) of the global population with drinking water, and in many of the regions are the only water source available. Consequently, they have been important for the regional economic development. The relatively rapid movement of water through high hydraulic conductivity preferential flow pathways in these systems increases the potential for them to be rapidly contaminated by surface sources. Kalhor et al. (73) provide a review of the typical contaminants, sampling methods, modeling, and remediation strategies peculiar to these systems, noting the complexity of modeling and monitoring this environment.

Megacities are an example of the vulnerability of groundwater quality to development. For example, isotopic studies indicate sewage-based contamination beneath several Southeast Asian megacities (76). Industrial contamination of soils with heavy metals serves as a source for groundwater contamination in Moscow (77). Groundwater extraction can induce transport of water from regions of high to low contaminant concentration, as noted for arsenic in Dhaka, Bangladesh (78, 79).

Andrade et al. (63) note that urban flooding can be a significant yet not well-monitored pathway for enteric pathogens (implicated in gastrointestinal disease) in groundwater. This is poorly understood and quantified given the belief that deep groundwater systems typically used for drinking water supply are pristine and unaffected by the mobilization of pathogens by storm water. (See the sidebars titled Mining and Groundwater Quality and Energy and Groundwater Quality.)

MINING AND GROUNDWATER QUALITY

Groundwater pollution due to mining is a global concern. Landscape disturbance can mobilize geogenic contaminants. Mining waste can be acidic and rich in metals, and through leakage and spills from tailing dams at the mines it can be a chronic pollution source. According to the United States Environmental Protection Agency's toxic release inventory (**https://enviro.epa.gov/triexplorer/tri_release.chemical**), metals mining is the number one source of water pollution in the United States, with more than 1.4 billion releases, whereas coal mining is #14, with more than 8 million toxic releases. These problems are also emerging in Central and South America, and in Africa, around iron, copper, gold, and lithium mines (80–84). Acid mine drainage is a pervasive problem around coal mines and metal mines (83). Legacy mining activities in North America, Europe, Australia, and Asia have left a significant, unattended legacy of such sources. Furthermore, throughout the world mining activities are intensifying to meet the demand related to electronics, batteries, and renewable energy. However, a synthesis of the global groundwater impact of mining is lacking (85–87).

ENERGY AND GROUNDWATER QUALITY

Energy production and storage, covering oil, gasoline, petroleum byproducts, volatile hydrocarbons, dense non-aqueous phase fluids, solvents, and coal fly ash, leads to groundwater pollution (88, 89). Hydraulic fracturing of shale gas bearing formations using horizontal wells has grown rapidly in the past two decades, leading to the following concerns: (*a*) stray gas migration into shallow aquifers (90), (*b*) contamination by hydraulic fracturing fluids from leaks and spills in wastewater handling (90), (*c*) increased seismicity due to the reinjection of residual wastewater in deep geologic formations (91), and (*d*) development of biocide-resistant microbes that transform frack fluid additives to compounds toxic to humans and ecology (90). A perceived risk, that fracking chemicals may migrate from the 0.5- to 3-km depth of injection to upper shallow aquifers used for water supply is not considered to be significant (90, 91). The lack of baseline data on aquifer conditions is cited as a major limitation to the detection and attribution of the impacts (90–92). Wide variations in methane concentrations in groundwater are noted in areas with intensive gas production as well as in areas with limited activity.

3. A HIDDEN RESOURCE

Groundwater and aquifers, due to their hidden nature, present a tremendous challenge to study and manage. A confident assessment of the global state of groundwater with regard to availability, quality, use, and recharge is difficult due to a paucity of spatially specific data. Consequently, current global assessments made using a mix of available aggregated observations, proxy data, and mass balance models tend to be skewed toward well-documented areas and are at best indicative of the relative situation in a subset of regions. At a smaller scale, areas where a significant degradation of the resource is evident tend to be better researched and documented in government reports and the news. In many such locations, data sets exist, models are developed, and an extensive archival literature provides a detailed analysis of the state and trends of the regional groundwater. Some other regions may have monitoring institutions with sufficient resources to measure and share data, although rarely with the sufficient levels of detail to understand the complex mechanisms affecting groundwater flow. Although challenges exist for all scales of groundwater modeling, we focus on uncertainties in global and regional groundwater assessments and the advances that have been made to address them.

3.1. Groundwater Data Gaps and Challenges

All global assessments of groundwater acknowledge the need for better data to quantify groundwater resource conditions (93). Large uncertainties in the volume, distribution, recharge, quality, and withdrawal of groundwater resources are noted across each segment of the literature we reviewed.

Soil/rock properties, water levels, or composition are measured at the borehole scale when directly measured, and at larger scales using indirect geophysical techniques, but rarely at scales longer than 1 km. Global assessments are based on discrete measurements and extrapolated with high uncertainty for all model parameters. For example, Jasechko et al. (94) base groundwater age estimates in 2017 on "only" 6,455 wells or point measurements around the globe. Fan et al. (12) base the global water table depth on more than 1.4 million points of measurements in North America and fewer than 431 sites for the entire African continent, highlighting the extreme paucity of information over a large area. Hora et al. (95) show that although publicly available groundwater level measurements seem to indicate that the aquifers are replenishing in South India, this is an artifact due to survivor bias, as wells with depleting water levels have dried up and are no longer part of the data set used for trend analysis. Thus, systematic bias in addition to uncertainty is a concern.

Knowledge on the state of groundwater quality is even more limited by the uneven distribution of measurements. Groundwater quality measurements are also point based but tend to be a minor subset of groundwater depth measurements due to relatively high analytical costs compared to measuring water level. Some analytical methods cover a suite of analytes, e.g., elemental analyzer or inductively coupled plasma-atomic emission spectrometry. However, there is no method for accurately measuring the range of possible water contaminants of interest. Certain types of contaminants, such as pesticides and PFAS, each include classes that in turn include discrete compounds, some of which can be binned and measured together, but others must be analyzed individually. In situ or real-time water quality monitoring is more expensive than a pressure transducer for measuring water level and is not possible for most analytes. The U.S. National Groundwater Monitoring Network includes more than 7,000 water level wells, but just under 2,000 water quality wells, and the temporal sampling is also sparser. These monitoring designs are at best indicative of the current state but are inadequate for understanding the fate and transport of contaminants or the human exposure pathways.

Technologies may play a role to fill this data gap. Remote sensing provides a global overview originating from a single source that is not impaired by multiple data standards (93, 96). The GRACE satellites, which allow for measurements over large regions that may be difficult or expensive to monitor in situ (97), provide an interesting advance. However, the >100,000 km^2 resolution GRACE data has limited utility for management decisions in most areas (98, 99). Integrating a variety of mass and energy balance using satellite and local measurements with GRACE data can provide higher resolution estimates of total water storage change, which is a proxy for groundwater mass change (e.g., 98, 100, 101). Other satellites can provide groundwater-relevant proxy data at a higher spatial resolution. For example, vegetation indices from Landsat and evapotranspiration from Moderate Resolution Imaging Spectroradiometer (MODIS) can be used to classify the persistence of shallow groundwater for groundwater-dependent ecosystems (102). Additional remotely sensed data, such as slope and drainage density, have been used to identify relative groundwater potential (103). Corresponding advances for deep aquifers and for water quality are lacking.

Despite these areas of progress, a central weakness in all global assessments of groundwater stress is obtaining groundwater extraction volumes that are accurate, concurrent, and at the appropriate temporal and spatial scale. Estimates of groundwater use are rather crude given that there is no organized monitoring or collection of data on pumping in most places. Most global studies rely on AQUASTAT values that are aggregated at the country scale and come from many different sources (93). The AQUASTAT estimates depend on when a study was conducted, which may be 5 or 10 years earlier, and their utility is unclear (e.g., 104). At the continental or country scale, the challenges are similar; e.g., in the United States, estimates of groundwater withdrawals are published by the U.S. Geological Survey only once every five years and at the yearly and county level (105). Consequently, current global estimates of water stresses, their projections, and their impact are plagued by considerable uncertainties, sometimes leading to the estimate of trends of the opposite sign compared to remote sensing measurements (106).

There is a need for institutional action on collecting and making groundwater data more accessible. Definition of standards is crucial for initiatives at multiple levels from governments to international organizations. Efforts have been made in that direction. IGRAC was founded by the United Nations in 2003 to "facilitate and promote world-wide exchange of groundwater knowledge and information to improve groundwater management," and led to the creation of the Global

Resource management: allocation and use of resources (e.g., water, land, minerals, or energy)

Risk: the probability of adverse impacts

Groundwater Information System and the Global Groundwater Monitoring Network to centralize monitoring data from various programs (**https://www.un-igrac.org**). The United Nations has also launched a water accounting program to define coherent and standardized water data standards (**https://wateraccounting.org/background.html**), an essential piece component of data to inform resource management. Nongovernmental organizations may help bridge the data gap. Start-ups, nonprofits, and large corporations are getting involved (107). In addition, citizen scientists and community-based monitoring have become more prevalent, but access to high-quality existing data collected for projects by scientists and consultants continues to be elusive (108–110). The data revolution is already transforming groundwater research, but the relevance of the data and the analytical methods to inform or transform groundwater management is an open question (111).

3.2. The Relevance of Groundwater Modeling

As direct measurements alone cannot quantify the state of the resource and risks associated with future climate and use conditions, groundwater models become an important tool to understand the dynamics and to inform risks and management. In the past, many estimates of aquifer safe yield were based on the estimates of average annual renewable recharge. These have evolved to consider spatial variability of aquifer properties, flow dynamics, and propagation of pollutants, together with recharge mechanism and abstraction, thanks to advances in groundwater modeling and computational power (e.g., 112). Detailed groundwater models at the local and regional scale are now well established, covering both flow and contaminant transport, and they rely on detailed, locally collected data on aquifer properties, recharge, point sources and sinks, and groundwater abstraction. They are typically calibrated to water pumping, water level, and water quality data. The application of such models is now quite routine by consultants, government agencies, and companies, with each application tailored to a particular purpose.

Larger-scale models naturally require data representing the larger domain. However, aggregation of data from small-scale studies can be difficult to obtain and compile. For example, assembling a superset of studies done by the US Geological Survey over the past 4 decades is challenging, despite publicly posted data sets and well-documented models. Combination of data and model parameters from smaller studies typically leaves a majority of the land area unrepresented; nonetheless, comprehensive models of the flow processes across large areas are regularly produced. For example, high-resolution models have been produced for the United States (113) and the world (12). In both cases, primarily the shallow aquifer is modeled, and the models can help inform interactions between climate, surface water, and shallow groundwater processes. The models lack an adequate representation of groundwater abstraction in part due to poor water use data.

Global groundwater modelers do not focus on groundwater hydrodynamics, but rather perform mass balance-based sustainability studies to quantify water stresses and risks. Most of their models focus on the interaction of precipitation with surface runoff generation, recharge estimation, and a crude representation of shallow groundwater. Some represent interactions with surface water bodies (98), but few actually encompass adequate groundwater abstraction (114) and simulation of deeper groundwater. Furthermore, subsurface lateral flows can be significant beyond watersheds (115), posing further challenges to groundwater modelers in terms of scale and processes to model. As a result, such models have limited utility for prediction or management. Rather, they are a valuable complement to the larger-scale analyses done using GRACE data as a milky lens on the global groundwater situation. The large uncertainties (2, 9, 93, 116) associated with global analyses may lead to different conclusions as to which regions are stressed (117).

To fully grasp the human impact on groundwater resources and the associated risk, it will be necessary to go beyond groundwater quantity assessments and consider groundwater quality challenges such as seawater intrusion and anthropogenic and geogenic contamination (118). This poses new challenges to the global modeling community if they wish to look at global groundwater sustainability from an actionable perspective. Well-constrained regional models are consequently important to develop, accompanied by appropriate data. This could then be followed by a global effort as a synthesis of the information that is generated. Support from national and international organizations to develop such a synthesis would be necessary for more useful regional and global analyses for all the areas of relevance to groundwater past, present, and future.

The United Nations Environment Programme (93) has argued that better data, ongoing monitoring, and improved modeling of aquifers systems are needed for sustainable management. This needs a proper quantification of bias, risk, and uncertainty in the data sets and the models that propagate that information (117). The scientific tools to do this exist (119). Nonetheless, stochastic hydrogeology is far from common practice due to institutional barriers and lack of incentives from the public and private sectors (120). Rubin et al. (120) remark that the main challenge may stem from the importance of "unknown unknowns," which may be greater than the uncertainty in subsurface flow parameters, in particular demographic trends and the drivers of human behavior toward extraction, pollution, and regulation.

4. MANAGING GROUNDWATER

Groundwater quantity and quality management become increasingly important as resources become stressed. Management decisions may be made at multiple levels, including the individual landholder, community leader, regional, agency, or national level. Each of these stakeholder types may have varying access to information with which to make their decisions, and differing motivations at the long-term and large spatial scales.

References 2, 121, and 122 provide some recent perspectives on groundwater management. Major interrelated goals for the sustainable management of groundwater resources include

- Quantity: arresting and reversing groundwater mining or depletion, accounting for impacts from climate variability and change
- Quality: maintaining and improving the quality of groundwater through appropriate pollution control and aquifer remediation
- Equity: equitable and efficient allocation of the resource, recognizing value of use and the human right to water, scarcity, ecosystem needs, and intergenerational access

Strategies to address water quantity management goals can be executed at local and government scales (see sidebar titled Groundwater Use, Monitoring, and Regulation: A Tale of Two States). Local practices include irrigation management by water use efficiency measures, crop selection that balances crop water demand with renewable water availability, and local managed aquifer recharge. Government-scale activities may include implementing permits to cap extraction based on safe yield, the use of market instruments, such as pricing and trading to motivate sustainable practices, and large-scale managed recharge or water banking. Groundwater quality management practices include protecting source water resources by restricting development in certain areas, limiting pollution loading by requiring discharge permits or best management practices, and remediation of aquifers where pollution is already a problem. Equity-related management decisions would be implemented at the government scale, to ensure equal access among present and future users. Groundwater is notably susceptible to the Tragedy of the Commons, and users with greater

GROUNDWATER USE, MONITORING, AND REGULATION: A TALE OF TWO STATES

During the 1987–1991 drought, reservoirs were depleted, groundwater pumping and farmer investment in water conservation increased, and California set up water banks and trading (123). During the 2015 drought, the governor of California mandated a 25% reduction in water use, except for agriculture, although it accounts for 80% of total water use. The lack of monitoring of agricultural well pumping meant the regulation would not have been enforceable. Consequently, significant increases in groundwater depletion were reported (124, 125). California introduced the Sustainable Groundwater Management Act that requires governments and water agencies to halt overdraft by the 2040s. Proposed reforms include data collection, modeling, and their Web access. Currently, groundwater use and quality data reporting and recording lag behind other US states. In 2016, fewer than 50% of the irrigation districts reported their water use as required (126). Kansas manages depletion in the High Plains aquifer (127, 128) by requiring measurement and reporting pump withdrawals (127). Kansas's Local Enhanced Management Area program introduced irrigator-driven regulatory proposals with governmental oversight in 2012. Between 2013 and 2017, water use was reduced by 31%, effectively stabilizing groundwater levels while maintaining farmers profit. This showcases the effectiveness of combining data collection, stakeholder engagement, and regulation (128).

capability to extract more water and from deeper wells typically do so without regard or regulation that would protect other users.

In the remainder of this section, we provide an overview of the challenges to implementing any type of management strategy given ubiquitous data gaps and system uncertainty, and challenges inherent to government-led interventions. We then discuss conjunctive use and specifically managed aquifer recharge, which are increasing in research popularity and potential impact.

4.1. All Management Strategies Rely on Understanding the System

The need to actively manage regional groundwater systems is now well recognized. However, regulatory and management frameworks vary across the world, and in most places, there is very limited or ineffective management of the resource, relative to the ideas and methodologies that are discussed for at least the past 40 years in the academic literature. The most pressing requirement for properly managing groundwater is understanding the state and dynamics of the system. Given the hidden nature of groundwater systems and typical lack of data, as discussed in this review, implementing effective management strategies is a challenge. This is compounded by the generally low economic value placed on groundwater, which leads to relatively few financial resources for local stakeholders to monitor and manage their water resources.

Quantifying the amount of water returning to deep aquifers and measuring (and reporting) groundwater extraction remain a practical challenge. Unfortunately, this uncertainty on both sides of the water balance is common in many groundwater systems, as discussed in previous sections. In most places in the world, data needed for model calibration are neither publicly archived, nor readily available in a usable form, even though their collection may be required for every well that is put in. Remote sensing and its integration with models, e.g., the GRACE type of analyses, purportedly address these challenges, but are primarily a tool to assess impacts as to total water storage change at large scales, and are not useful for effecting changes in groundwater quantity in the absence of knowledge of the sources that could be regulated.

Similarly, for water quality management, data on pollutant loadings (especially for agricultural and urban nonpoint sources that are a major source of nutrients, salinity, and pathogens) for shallow aquifers, and of the associated fate, flow, and transport, are rather limited. In all cases, local management efforts may periodically collect and update these data sets, but analyses of such processes at regional scales considering surface and groundwater dynamics continue to be rare. Consequently, we consider the regional- to continental-scale groundwater management challenge to be dominated by the need to collect, access, and analyze such data, irrespective of the underlying regulatory or management framework.

4.2. Inherent Challenges for Government-Led Management

There are time and space challenges associated with establishing reasonable groundwater management practices. Because groundwater system responses to a new forcing may take hundreds of years to reach a new equilibrium, management typically occurs during the transition period where the impacts of the human action may be difficult to observe. Hydrologic models can be used to project impacts into the future. However, developing and applying models, engaging decision makers, and accounting for uncertainty are challenges for practical application. Even if sustainability is a management consideration, the data and methods may not be available to assess the extent and timing of implications of groundwater pumping or a contamination event.

Spatial scales relevant to management often correspond to political jurisdiction, rather than groundwater basin or aquifer extents. Alley et al. (129) suggest the consideration of storage, recharge, water use, and climate as better determinants of groundwater sustainability, while considering the relevant management scales, rather than a coarse global view. This is important for resource allocation and for taking responsibility for actions impacting groundwater availability or contamination. Groundwater pumping or a contaminant plume in one region may ultimately impact groundwater or surface water resources in another management jurisdiction. Transboundary aquifers are a major topic of hydrogeological and political studies, with no clear standard for legal resolution (130, 131).

Another challenge inherent to government-led groundwater management strategies is the need to balance water security with other government objectives, such as economic and food security. The variety of management efforts proposed typically must balance political, economic, and environmental concerns, and can therefore be difficult and slow to implement. In some low-income regions, including parts of sub-Saharan Africa, research is promoting the potential sustainability of increasing groundwater use (132, 133). However, several countries have recently focused on expanding irrigated area by smallholder farmers (134); for example, the Agricultural Transformation Agency in Ethiopia is investigating small photovoltaic powered irrigation systems (135). The competing government objectives often lead to food security or economic development goals trumping groundwater sustainability, given that intergenerational activity is invariably harder to sell politically.

Water and food security linkages are being looked at from a global perspective (136, 137) through the lens of trade in virtual water, i.e., the water embedded in the grains or other crops that are traded on the global market. These transactions are driven more by market supply and demand for agricultural commodities and the associated government policies than by a direct consideration of water sustainability (see sidebar Solving India's Groundwater Challenge). One viewpoint advanced is that groundwater depletion in arid regions that are net exporters of crops could be relieved if agricultural intensity were reduced in these areas. Indeed, in many cases, e.g., Israel and California, a transition to higher value crops with higher efficiency irrigation has already begun. However, in many cases it is observed (143, 144) that the water saved by improving irrigation efficiency may then be used to expand the irrigated area. Consequently, the beneficial reduction in groundwater depletion may be dramatically reduced.

SOLVING INDIA'S GROUNDWATER CHALLENGE

Over the past 50 years, India achieved food self-sufficiency in cereal production. A government procurement and distribution system promoted rice and wheat cultivation. Much of the production takes place in arid regions, where irrigation using groundwater contributed to higher crop yields. Government subsidies include a fixed annual charge for electricity for pumping. The resulting proliferation of groundwater use led to groundwater depletion to depths of 60 to 200 m below surface as compared to 5 to 10 m below in the late 1990s. Solutions include increasing aquifer recharge through check dams, higher irrigation efficiency, pricing electricity consumption, and shifting crops. Shifting where rice and wheat are procured could eliminate groundwater depletion in the stressed regions, while increasing aggregate net farm income (138). Irrigation efficiency improvements at the farm level (139) and switching to lower water-demand crops (140) can help, but their impact may be moderated by farmers choosing to expand irrigated areas (141). Experiments on electricity pricing reform (142) suggest that payments for conserving electricity are a useful pathway for transition; increasing artificial recharge may have a modest impact.

Water quality is similarly balanced with these other objectives and is noted by variations in regulations on industrial and agricultural pollutants. In areas with low fertility soils, or where yields are limited by nutrient deficiencies and pests, management efforts are likely to promote application of agrochemicals in the interest of food production and increasing farmer income, rather than prioritizing protection of groundwater quality. There is in fact limited legislation that impacts agricultural application or release of nutrients (145), leaving management decisions largely to the individual land owner. Precision agriculture can help address both food production and water sustainability; however, so far, the cost of these practices restricts adoption to high-income regions and even further to high-value crops.

4.3. Managing Quantity and Quality Through Conjunctive Use

Management of groundwater in conjunction with surface water is known as conjunctive use management. Optimization of extraction rates and timing from multiple water resources provides a model framework for water users and managers. Optimization objectives for conjunctive use plans may be based on reliability (146), economics (147), environmental conditions (148), or their combination (149). The data gaps discussed earlier are a notable challenge of conjunctive use planning, because one must accurately simulate interactions between both the surface and groundwater systems. Because uncertainties exist in the physical systems, data-based statistical and machine learning computational approaches are becoming more common (150).

Conjunctive use can be applied in scenarios with contaminated water sources both to protect users and to improve water quality within the reservoir. Solutions considered to minimize exposure include (*a*) a judicious selection of the water sources to use, (*b*) monitoring to identify the potential occurrence of the contaminants and their changes, and (*c*) treatment of water prior to use. Conjunctive use including surface water, saline water, and even multiple groundwater sources can be especially valuable in hydrologic systems with heterogeneous geogenic contaminants, such as arsenic in the deltaic aquifers in Bangladesh. Extraction from safe well locations and depth intervals must be optimized to meet demand while keeping flow rates below a threshold where arsenic may be mobilized.

Although there have been significant advances in optimization models for groundwater management at the local to regional scale, most of these models are difficult to practically implement given that they typically address a rather specific water quality or quantity management goal, and do not directly connect to the institutional management structure or ability. Elwell & Lall (151) and Lall & Lin (152) suggest modeling the groundwater bodies including water quality and pollution sources, as well as the regional institutional structure to devise optimization strategies for determining safe and economical regional development of groundwater resources. References 153–155 provide reviews of related groundwater management models. Recent droughts in Australia and California and prior efforts in Arizona are leading to discussions of market-based regulatory structures for groundwater management. At the country scale, Australia is the closest to adopting conjunctive use planning; however, political challenges continue to impede the progress (156).

4.4. Managed Aquifer Recharge

Transfer and storage of water to aquifers is an attractive conjunctive use option given that aquifers are not subject to as much evaporation as surface reservoirs and allow the land to be used for other purposes. Where surface water or treated wastewater is available, managed aquifer recharge (MAR) is being promoted as a component of conjunctive use water management (157, 158).

MAR implementation has increased at a rate of 5% per year; however, this is lower than the rate of increase in groundwater extraction (158). Stefan & Ansems (159) provide a web-based updated global inventory of MAR applications. Dillon et al. (158) provide a 60-year perspective on MAR at the global scale, estimating that MAR has reached 10 km^3/year, which is approximately 1% of the global extraction rate or 2.4% of groundwater extraction in countries reporting MAR. Although uptake is slow, the potential for MAR continues to be promoted in the literature at both large, government scales and as small, distributed systems implemented at the household scale.

MAR can be done through riverbank filtration (practiced largely in Europe), through land application or pumping below existing surface water reservoirs during surplus periods, or through treatment of wastewater followed by injection through wells that are also used for pumping or through check dams to infiltrate surplus monsoon rainfall (e.g., in South Asia). It is seen as an integral piece of a strategy for conjunctively managing surface and groundwaters at a regional scale. There is very little activity reported for MAR in Latin America, the Caribbean, China, and South Africa.

MAR associated with urban centers, combined with wastewater treatment using membrane bioreactors or other methods, emerged as a strategy in the United States, Europe, and Asia starting in the 1990s and was sometimes coupled with aquifer thermal energy storage in Europe (158). These developments aim to manage both the quantity and quality of recharge with the opportunity of subsequent water extraction and reuse in the urban setting. By contrast, the check dam–based efforts in India since the 1970s recharge stormwater into shallow aquifers with no explicit attempt at water quality management. However, their primary use is to provide water for supplemental irrigation and only secondarily to support rural drinking water supplies. Although the total number of such dams in South Asia is not known, an analysis of the news media and of government budgets for the purpose of constructing them indicates that they have had a high growth rate over the past two decades. They may constitute a significant modification of the surface and subsurface hydrological cycle in South Asia that is not well measured as to either quantity or quality of water modified, or in terms of impact on vector-borne disease.

Regulatory policies for MAR have evolved in several US states (e.g., Arizona, California, and Florida) and in Australia, while India has also developed a policy manual for check dams, but no regulations. Typically, water quality for injection is regulated, and permits may be given out for both recharge and recovery wells. Most recently, San Diego, California, has introduced an interesting legislation that allows individual entities to bank treated stormwater or wastewater and to also market the resulting credits. The past existing permits for wastewater treatment by large businesses are included in this credit system. This suggests that decentralized wastewater treatment and storage using modular or mobile membrane bioreactors could emerge with trading markets for wastewater treatment and reuse that use MAR as the storage strategy, and also offer economic wastewater treatment and pollution control that avoid the need to replace aging sewer infrastructure or malfunctioning septic tank systems used for land treatment of wastewater.

Although MAR has been increasing in the urban context in Europe, Australia, and North America, and in the rural context in South Asia, several technical challenges remain. Clogging and fouling of soils, river banks, and wells are an endemic problem. As recharge water interacts with sediments and groundwater, geochemical reactions can occur that mobilize or transform contaminants in the shallow groundwater. Significant research has been ongoing on addressing these aspects. Where active pumping is not used for recharge, the locations where rapid recharge and filtration could occur using sandy soils are rather limited. Large land areas are also required for land application of surplus waters, thus obviating the advantage over surface reservoirs. The ability to recover the treated, recharged water by the same user when desired also requires strong local oversight and enforcement of rights and permits.

5. CONCLUSION

The burgeoning volume of published research and media attention to groundwater depletion worldwide underscores the critical sustainability challenge posed by changes in the state of our groundwater resources. The GRACE analyses provide vivid visuals of the scale of depletion. Yet, the impacts and management challenges of depletion are largely local and regional. Perhaps the global attention to these regional challenges will stimulate a better understanding of the drivers, as a prerequisite for the social and technical changes needed to reverse the trajectory. Even so, given the cost associated with reversing chronic contamination that emerges as a cumulative effect in space and time, the challenge posed by the anthropogenic contamination of groundwater and the mobilization of geogenic contaminants as water use increases may really emerge as the bigger challenge. Climate variability and change amplify these adverse dynamics of groundwater outcomes as access to surface water is limited and contaminants are mobilized. Several of the resource challenges can be solved, but require spatial specific data and analyses that connect drivers to outcomes, and go beyond regulatory monitoring to support causal analysis. As data science takes a more prominent role in virtually all human functions, we hope that the importance of data and model synthesis in this field will transcend from academic research to routine application. Much of this has happened in the past several decades, but much needs to be done, and tough political decisions for resource management and regulation may become more tenable as the data-induced uncertainties are reduced. Using climate change adaptation as a driver to better understand and act on groundwater issues would be opportune in this regard.

SUMMARY POINTS

1. The availability of high-quality groundwater is decreasing as abstraction continues to increase globally, especially in arid agricultural regions, and in urban centers. However, detailed data to quantify these trends remain sparse.
2. Pollutants from agriculture, industry, mining, energy production, and legacy landfills are an increasing threat to groundwater. The mobilization of geogenic contaminants such as arsenic or fluoride is an ever-growing menace for drinking water, notably in South and East Asia. The extent and issues associated with emerging contaminants, including pharmaceuticals, solvents, and glyphosate, remain largely unknown.

3. Agriculture remains the dominant consumptive use of groundwater and a significant source of nongeogenic contaminants. Following the limitations of irrigation efficiency notions to reduce water use, managing crops and withdrawals is critical for groundwater futures and for food security.
4. Significant scientific advances provide us with a window into some global groundwater conditions, yet data inadequacies as to the coupled human-natural dynamics hamper the rigorous assessment of regional and larger groundwater dynamics. Increased monitoring of the coupled natural and human system improves modeling capabilities and enables evaluation of sustainable groundwater management practices.

FUTURE ISSUES

1. Rising sea levels may increase saline water intrusion in groundwater systems, especially as growing coastal cities pump more groundwater. This will be a significant threat for coastal, urban populations who rely on groundwater, especially from Karst aquifers. Climate change may also induce additional groundwater pumping to support highly intensive agriculture for a growing global population. The extinction and pollution of groundwater in both settings may be the trigger for mass human migrations, and loss of species as perennial groundwater-fed environments are starved.
2. Renewable energy may soon be very inexpensive, and this may either accelerate groundwater use or make desalination and wastewater reuse more affordable, leading to two very different directions for future groundwater.
3. The demand for better information on groundwater quantity and quality trends and how best to equitably manage them is growing worldwide. This should drive improvements in methods to collect data on such systems, especially on groundwater use and quality. Monitoring millions of wells in a country, quantifying their collective impact over time and space, and contextualizing that impact with aquifer properties and institutional actions will likely stay a challenge. Seeing a reversal of current trends of depletion and quality degradation in the most challenged places is unlikely given the current political and institutional factors and the limited ability to develop alternate solutions in these regions.

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