Aude-Sophie Rodella
Esha Zaveri
François Bertone
Editors

The economics of groundwater in times of climate change

The hidden wealth of nations

WORLD BANK GROUP

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This publication received the support of the Global Water Security & Sanitation Partnership (GWSP). GWSP is a multidonor trust fund administered by the World Bank's Water Global Practice and supported by Australia's Department of Foreign Affairs and Trade, Austria's Federal Ministry of Finance, the Bill & Melinda Gates Foundation, Denmark's Ministry of Foreign Affairs, the Netherlands' Ministry of Foreign Affairs, Spain's Ministry of Economic Affairs and Digital Transformation, the Swedish International Development Cooperation Agency, Switzerland's State Secretariat for Economic Affairs, the Swiss Agency for Development and Cooperation, and the U.S. Agency for International Development.

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Please cite the work as follows

Rodella, Aude-Sophie, Esha Zaveri, and François Bertone. 2023. "The Hidden Wealth of Nations: The Economics of Groundwater in Times of Climate Change." Washington, DC: World Bank. License: Creative Commons Attribution CC BY 3.0 IGO

Cover, report design and visualizations by Voilà: | chezVoila.com

Acknowledgments

This report was prepared by a team led by Aude-Sophie Rodella (TTL, Senior Economist), Esha Zaveri (co-TTL, Senior Economist), and François Bertone (Senior Groundwater Specialist) under the strategic guidance and general direction of Juergen Voegele (Vice President, Sustainable Development Practice Group), Saroj Jha (Global Director, Water Practice), Jennifer Sara (Climate Change Global Director, formerly Water Global Director), Soma Ghosh Moulik (Practice Manager), Yogita Mumssen (Practice Manager) and the management of the Water Global Practice.

In addition to research completed by the authors, this report is based on background papers, notes, and analyses prepared by a core team of internal and external collaborators.

Internal collaborators included (in alphabetical order): Soumya Balasubramanya (Senior Economist), Edoardo Borgomeo (Water Resource Management Specialist), Christian Borja Vega (Senior Economist), Si Gou (Water Resources Management Specialist), Tejasvi Hora (Consultant), Hanan Jacoby (Lead Economist), Lucy Lytton (Senior Groundwater Specialist), Siobhan Murray (Geographer), Jane Park (Consultant), Précila Rambhunjun (Consultant), Pedro Rodriguez Martinez (Consultant), Seojeong Oh (Consultant), Ali Sharman (Consultant) and Karen Villholth (Consultant).

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The team is grateful to colleagues from the World Bank for their helpful inputs and suggestions at various stages of the book’s development, including (in alphabetical order): Gabriela Azuela, Bogachan Benli, Meskerem Brhane, Eileen Burke, Gaia Hatzfeldt, Sarah Keener, Amjad Khan, Christina Leb, Talajeh Livani, Sanjay Pahuja, Gustavo Saltiel, Amal Talbi, Pieter Waalewijn, Marcus Wishart and Fan Zhang.

The team was fortunate to receive excellent advice and guidance from the following peer reviewers at various points in the report preparation process: Richard Damania (Chief Economist, Sustainable Development), Abedalrazq Khalil (Lead Specialist and Program Leader), Genevieve Connors (Practice Manager), Giovanni Ruta (Lead Environmental Economist), Elisabeth Lictevout (Director, International Groundwater Resources Assessment Center), Dorte Verner (Lead Agriculture Economist). The team also benefited greatly from the feedback provided by the report’s external advisers at various key points during the report preparation process: Alan MacDonald (British Geological Survey), Robert Reinecke (University of Potsdam), and Veena Srinivasan (Water, Environment, Land, and Livelihoods Labs).

The World Bank Water communications, knowledge, and publishing teams, comprising Erin Barrett, Meriem Gray, Sarah Farhat, Zubedah Robinson, and David Gray, provided valuable guidance for turning a manuscript into a finalized report. Bruce Ross-Larson provided excellent editorial support and, with Joe Caponio, edited the report. Francis Gagnon and the team at Voilà: provided skillful information design and designed the report.

Finally, Georgine Badou and Kanny Diaby provided helpful administrative support for which the team is grateful.

This work was made possible by the financial contribution of the Global Water Security and Sanitation Partnership (see https://www.worldbank.org/en/programs/global-water-security-sanitation-partnership) of the Water Global Practice, World Bank Group.

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Abbreviations

ACLED	Armed Conflict Location and Event Data Project
AEZ	Agricultural Export Promotions Zone
IGRAC	International Groundwater Resources Assessment Centre
IPCC	Intergovernmental Panel on Climate Change
FAO	Food and Agriculture Organization of the United Nations
FEWS	Famine Early Warning Systems Network
FLW	Food lost or wasted
GDE	Groundwater-dependent ecosystem
GEF	Global Environmental Facility
GHG	Greenhouse gas
GRACE	Gravity Recovery and Climate Experiment
GWS	Groundwater storage
HAZ	Height-for-age-Z score
IPCC	Intergovernmental Panel on Climate Change
LSM	Land-surface model
MAR	Managed aquifer recharge
MNA	Middle East and North Africa
NASA	National Aeronautics and Space Administration
NBS	Nature-based solution
NGO	Non-governmental organization
SAR	South Asia region
SDG	Sustainable Development Goal
SSA	Sub-Saharan Africa region
TBA	Transboundary aquifer
TWS	Terrestrial water storage
UNEP	United Nations Environmental Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children's Fund
USGS	United States Geological Survey
WHO	World Health Organization

Summary

Groundwater is our most important freshwater resource. But the lack of systematic analysis of its economic importance has evaded attention from policymakers and the general public—threatening the resource. Groundwater provides 49 percent of the water withdrawn for domestic use by the global population and around 43 percent of all water withdrawn for irrigation. This report offers new evidence that advances the understanding of groundwater's value, showing how groundwater is a major asset in a country's resource portfolio—but also the costs of its mismanagement and the opportunities to leverage its potential. In a new contribution from this research, a global aquifer typology has been developed and validated. It considers key aquifer characteristics that matter for resilient development and poverty reduction—determining the economic accessibility of the groundwater resource to individual farmers, its sustainability, and buffering capacity of the aquifer to seasonal variations and climate shocks. Along with other data sources, it enables novel global economic analysis.

New analysis shows that what groundwater lacks in visibility, it makes up for in value. At the global level, groundwater can buffer a third of the losses in economic growth caused by droughts. It is especially important for agriculture, where groundwater can reduce up to half of the losses in agricultural productivity caused by rainfall variability. By insulating farms and incomes from climatic shocks, the insurance of groundwater translates into protection against malnutrition: lack of access to shallow groundwater increases the chances of stunting among children under five by up to 20 percent. In Sub-Saharan Africa, untapped groundwater irrigation potential could be key to improving food security and poverty reduction. Little land is irrigated there, but local shallow aquifers represent over 60 percent of the groundwater resource, and 255 million people in poverty live above them.

But groundwater overexploitation exposes economies to exponential risks—including maladaptation. Globally, major alluvial aquifers account for more than 60 percent of groundwater depletion embedded in international trade—including from regions with transboundary aquifers, adding further complexity and urgency to their management. In the Middle East and South Asia, up to 92 percent of transboundary aquifers show signs of groundwater depletion. The effects of this depletion are already painfully felt in South Asia, where groundwater once provided an agricultural revenue advantage of 10-20 percent, a benefit now disappearing in areas affected by depletion. In Sub-Saharan Africa, where groundwater has been underused given its potential, expanding solar pumping without adequate safeguards could threaten rural livelihoods relying on groundwater-dependent ecosystems. A hidden risk that is becoming more visible comes from deteriorating groundwater quality because of rapidly expanding urban areas, unregulated industrial sites, and inadequate agricultural practices. Harder to measure, this quality risk presents a growing threat to groundwater sustainability and the benefits it bestows.

Faced with growing demand, groundwater's specific features prime it for overexploitation in a classic tragedy of the commons—with exponential impacts disproportionately affecting the most vulnerable. It doesn't have to be that way. The recommendations are informed by greater understanding of groundwater's benefits and costs articulated around a framework of information, incentives, and investments and their corresponding policy levers. Two key dimensions are important. First is how the type of aquifer shapes the potential uses. And second is the country and regional degree of groundwater abstraction, from those who have underused the resource and have yet to harness its potential to those who have overexploited it and suffer the damaging consequences. The findings also inform the issues policymakers confront when attempting to align private and social opportunity costs of groundwater use. Urgent cross-sectoral action and high-level political mobilization are needed.

Note. All data used and produced for this report are or will be available at: https://wbwaterdata.org/

1

Valuing hidden wealth

Untapped or overdrawn, groundwater is a critical asset for poverty reduction, resilient growth, and climate adaptation. It was valued by ancient civilizations, which relied on groundwater for their water supplies, as the Romans did, even when building cities close to rivers.[1] Groundwater today, and more so in the future, will be a foundation for adapting to climate change. It provides 49 percent of the volume of water withdrawn for domestic use by the global population[2] and around 43 percent of all water withdrawn for irrigation, watering 38 percent of the world's irrigated land.[3] Its unique economic attributes, including its common-pool nature, are a blessing—and a curse. And its characteristics determine its present and long-term uses and possible negative spillovers. These need to be brought out of the shadows for the resource to yield its potential and be managed adequately.

A

Groundwater's economic attributes are a blessing —and a curse

Groundwater is key to water supply and agriculture and, thus, to food security: ranging from overexploited to underused, the level of its use varies greatly across regions. In the Middle East and South Asia, where irrigation has been a cornerstone of agriculture, up to 55 percent of irrigated lands use groundwater. In Sub-Saharan Africa, where less than 5 percent of agricultural land is irrigated, this figure comes down to less than 7 percent of irrigated lands using groundwater (figure 1.1). Groundwater abstraction has played a major role in accelerating food production and food security globally since the 1960s.[4] Of more than 500 of the world's largest cities, more than half have groundwater as part of their water portfolio.[5] More than 80 percent of large cities in the Middle East, South Asia, and Central Asia rely on groundwater as their main source. In Sub-Saharan Africa, around 44 percent of the population relies on groundwater for drinking. And on average, a quarter of the urban population in the region relies on groundwater. In countries like Nigeria, this reliance rises to close to 60 percent (figure 1.2). Such reliance highlights how groundwater is critical for water supplies—and how important it is to protect its quality.

Figure 1.1
Groundwater share of irrigated areas

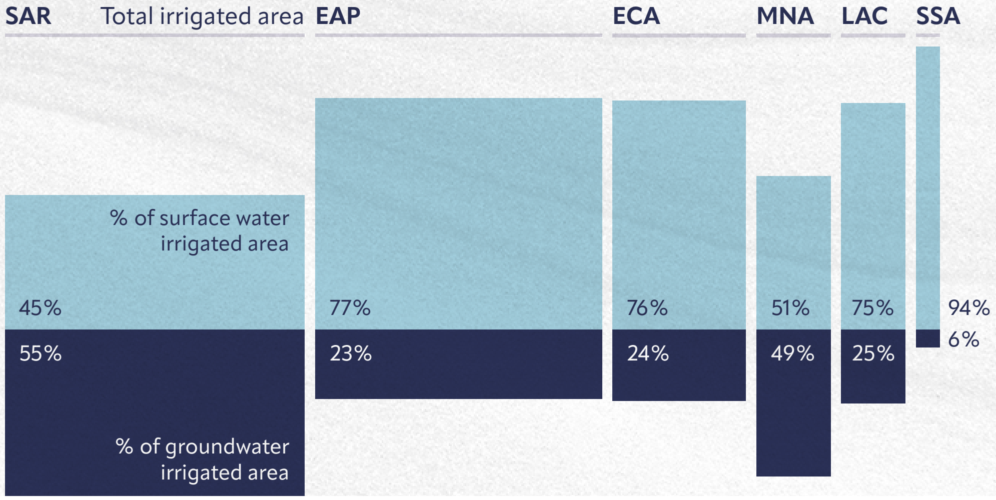
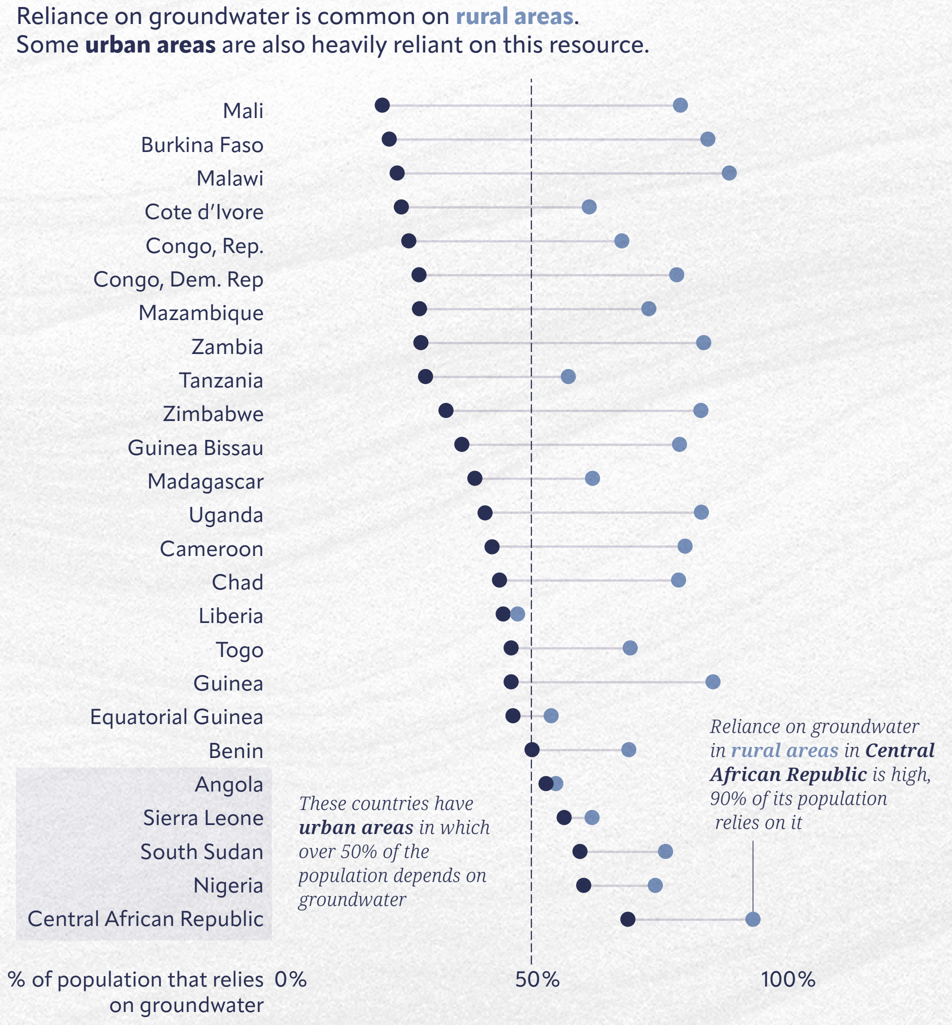


Figure 1.2

Percentage of urban and rural populations relying on groundwater for their water supply



Source: Latest household survey available, WHO/UNICEF Joint Monitoring Program.

This report shows that groundwater is a key asset in a country's portfolio to reduce poverty and promote resilient and equitable growth. Until now, groundwater's wealth has been underestimated, leaving it undervalued and taken for granted. Groundwater's hidden nature and unique characteristics further contribute to undervaluing the resource. Indeed, like the Water-Diamond paradox popularized by Adam Smith, whose origins are even more ancient (See Plato's dialogues—Euthydemus[6]), groundwater is critical to many key services and yet is often taken for granted, with few considerations for how this life-sustaining common-pool wealth should be best used, managed, and protected.

Using banking as an analogy, groundwater recharge can be equated with income and groundwater withdrawal with expenditure. To achieve balance, natural discharge and withdrawals should not exceed recharge. If they do, overextraction could compromise the long-term use of groundwater. Bankruptcy would occur if overextraction were also to jeopardize the "inheritance" of this wealth. Beyond the physical compromising of the resource, economic accessibility could be compromised at lower thresholds, with severe poverty and equity consequences.

Groundwater is a common-pool resource, reflecting its open and relatively easy access by individuals for some aquifer types. Common-pool resources are rivalrous in consumption, meaning that when one person uses such a public good, it can interfere with the ability of others to use it. It is also non-excludable to some extent, particularly in an open-access situation—meaning that it is costly or impossible to prevent potential users from tapping the resource. If each of those users seeks to maximize groundwater use, two key implications follow. First, unfettered access leads to unfettered competition. Second, with multiple users at scale, this competition can undermine the benefits and services groundwater provides to people, economies, and ecosystems in and outside the areas of use, with exponential consequences. Faced with growing demand, those features prime groundwater for overexploitation in a classic "tragedy of the commons," on hypercharge because of climate change (see Annex 2 on what economic theory says about groundwater).

Accessing groundwater depends on how far it is below the surface and on the cost of drawing it—both shaped by the type of aquifers. Key aquifer characteristics matter more directly for resilient development and poverty reduction—determining economic accessibility of the groundwater resource to individual farmers, its sustainability, and buffering capacity of the aquifer to seasonal variations and climatic shocks. In a new contribution from this research, a global typology considering those dimensions has been developed and validated, enabling novel global economic analysis. This global dataset consolidates, extends, and refines existing global datasets to bolster the understanding of aquifer types and their potential risks.[7] Those characteristics also matter for the management approaches required to facilitate long-term sustainability,[8] reap the expected benefits,[9] manage the relationship between individuals accessing a common-pool resource,[10] and foster successful collaboration between local users for aquifer management.[11] Two aquifer types, local shallow and major alluvial, are priorities for development thanks to their potential for individuals to tap. (See box 1.1 on types of aquifers and development implications.)

Economic accessibility—determined by capital investments and pumping costs to tap groundwater—has poverty and equity implications. Economic accessibility is primarily defined by groundwater depth, with 8 meters as a technical threshold allowing lower-cost surface pumps. Greater depths require submersible pumps at higher costs. Surface motor pumps and their declining costs have expanded groundwater use in South Asia. This threshold has important poverty implications, with rural poverty increasing by 10 percent in areas below this 8-meter cut-off.[12] Lowering the water table below this 8-meter threshold excludes users who can't afford additional drilling to keep pumping their drying wells. A second economic dimension pertains to the marginal cost of pumping, principally for energy to lift water, which increases with the depth of the water table. Lowering the water table through overextraction implies that poorer users will be priced out by users capable of paying for the energy. In theory, prohibitive marginal pumping costs constrain further declines in the water table.[13]

Certain types of aquifers are more exposed to the drawbacks of the common-pool characteristics of groundwater. In local shallow aquifers just below the surface, pumps operated from the surface make groundwater economically accessible to individual farms and households. Local shallow aquifers offer the most potential from a development perspective, particularly in Sub-Saharan Africa, and have smaller overexploitation risks than other aquifers. In contrast, the characteristics of major alluvial aquifers expose them to overexploitation. These aquifers are typically under river flood plains, and the amount of water drawn can be considerable. For them, drilling more than 50 meters down is typically required, and boreholes can often reach 200 meters down. The deep pumping increases the extraction costs—and thus, who can access groundwater. In more complex aquifers, typically in interconnected rock formations, exploration and even deeper drilling and pumping push the costs beyond the resources of individuals or groups and require governments to step in.

Box 1.1

Types of aquifer shape potential groundwater uses and risks for development and resilience

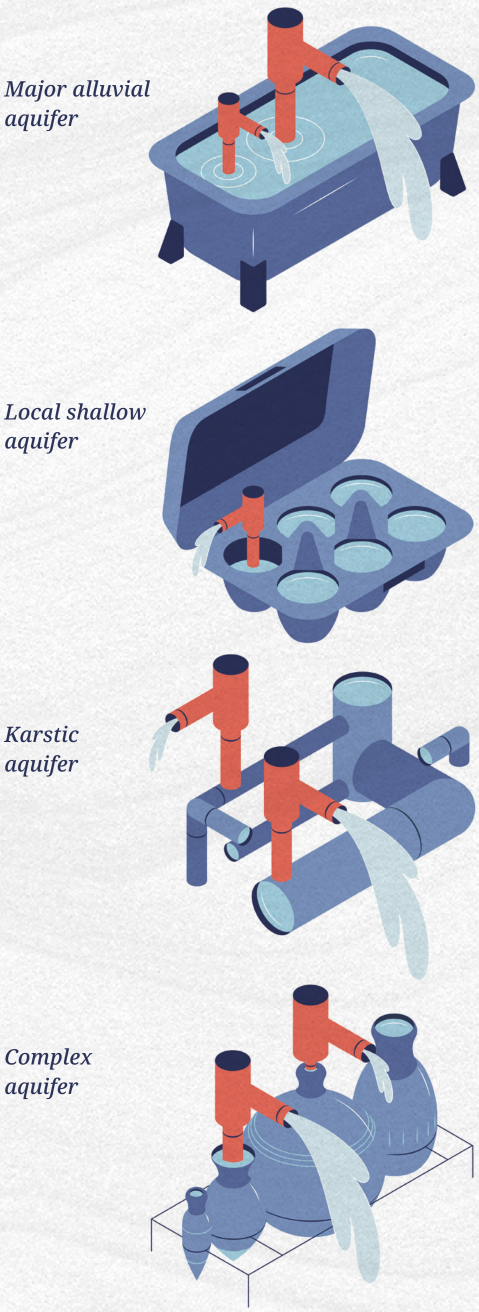
Until now, a systematic and data-supported approach has been missing to capture key aquifer characteristics that matter more directly for resilient development and poverty reduction. Indeed, determining the economic accessibility of the groundwater resource to individual farmers, its sustainability, and buffering of seasonal variations and climatic shocks has not been prioritized, contributing to the undervaluation of groundwater's critical contribution to development.

A new global dataset was developed and validated around four main types of aquifers, capturing those key characteristics to help inform policymakers to plan and manage groundwater for resilient development and poverty reduction. It consolidates, extends, and refines existing global datasets to bolster understanding of the aquifer types and their potential risks (see Annex 1 for detailed definitions). As represented in box figure 1, in large aquifers made of unconsolidated sediments, extraction and recharge behave similarly to water stored in a massive bathtub. And in fractured/weathered hard-rock aquifers, they behave like water stored in pockets of an egg carton. Whether a given region mostly has bathtub or egg-carton aquifers offers preliminary insights into the accessibility and potential of groundwater. Indeed, understanding those key aquifer characteristics has implications for the potential uses of groundwater and the types of risks and externalities to consider. Those characteristics also matter for the management approaches required to facilitate long-term sustainability,[1] reap the expected benefits,[2] manage the relationship between individuals accessing a common-pool resource,[3] and foster successful collaboration between local farmers for aquifer management.[4]

Box figure 1

Bathtubs, egg cartons, and complex and karstic aquifers

Source: Adapted from USGS (1999) and Beattie (1981).



[1] Beattie 1981; Fishman et al. 2011; Cuthbert et al. 2022.
[2] Edwards 2016.
[3] Beattie 1981.
[4] Shah 2010.

Two typologies describe the aquifers accessible to individuals, where the geology risk is limited (water wells and boreholes systematically find a minimum of groundwater) and the investment cost is minimal (water wells and boreholes are of limited depth):

- **Major alluvial aquifers** are massive bathtubs. They do not respond much to local rainfall. If pumping exceeds the recharge, the water table is gradually drawn down over decades—like a bathtub that's leaking faster than a tap can fill it. Major alluvial aquifers are easily accessible to individuals through simple boreholes with little risk. Their geomorphologic homogeneity often means they are tapped for only a few activities (usually irrigation).

- **Local shallow aquifers** are egg cartons, typically situated in weathered and fractured rock overlying parent non-weathered rock. They are typically shallow (often less than 50 meters) and vary widely in permeability and storability. As a result, they often function as small individual aquifer units. Local shallow aquifers are easily accessible to individuals through traditional open wells. Because they are local, the impacts of pumping them are local.

Two typologies describe the aquifers requiring institutional support to access the resource, i.e., where geology risk is high, borehole siting requiring high technicity and investments and risk of not hitting the expected groundwater rate is high, or where the investment cost is high due to the depth of the boreholes:

- **Complex aquifer systems** are large aquifers in consolidated geological formations. They mostly are superposed or juxtaposed sedimentary or volcanic terrains that are more or less permeable. They may have significant tectonic or geomorphological features, making them complex and partially compartmentalized. Freshwater is often pumped at depths of several hundred meters via complex boreholes.

- **Karstic aquifers** are complex systems with caves, sinkholes, and underground streams. Water circulates in a "pipe jumble" of discrete conduits that range from a few centimeters in diameter to tens of meters in diameter. They are vulnerable to contamination (as recharged via sinkholes), and water flows are very concentrated. Due to the large extent of most karst basins, the local groundwater can be considerable. But it is accessible only to institutions with the financial and technical capacity to explore the karst, identify the conduits, and construct boreholes, which could be hundreds of meters deep.

Environmental externalities affecting groundwater quality and dependent ecosystems also matter for poverty, intergenerational equity, and sustainable development. Externalities—the costs transferred to society not borne directly by the related activity—can compound the welfare effects. Those externalities include the loss of groundwater-dependent ecosystems, land subsidence, and deteriorated quality (saline intrusion, fertilizer contamination, new emerging pollutants). Environmental effects are determined by the rate of groundwater extraction and policies shaping pumping, drilling, and other behaviors-notably contamination control-through incentives. Indeed, groundwater extraction entails an intensive margin (pumping) and an extensive margin (well and borehole drilling). Either or both may be affected by agricultural policies. Given the costly investment involved, welfare implications may be greatest for the drilling margins.[14] Environmental externalities are also shaped by policies not considering social costs, including groundwater quality.

The pumping costs for groundwater economic accessibility have important poverty and equity implications. Two dimensions define this economic accessibility due to the technology and pumping costs involved in groundwater extraction.[15] The first economic dimension: water at a depth of up to 8 meters, is a technical threshold allowing lower-cost surface pumps; greater depths require submersible pumps at higher costs.[16] Surface motor pumps and their decreasing costs have expanded groundwater use in South Asia. Lowering the water table below this 8-meter threshold excludes users who can’t afford additional drilling to keep pumping their drying wells. A second economic dimension pertains to the marginal cost of pumping, principally for energy to lift water, which increases with the depth of the water table. Lowering the water table through overextraction implies that poorer users will be priced out by users capable of paying for the energy. In theory, further decline of the water table is constrained by prohibitive marginal pumping costs.

Box 1.2

Who owns groundwater?

Groundwater has no built-in ownership, as it is naturally an open-access common-pool resource. However, with humans using groundwater for their needs since immemorial times, the question arose: Who does it belong to, and of course with more intense use, this question became even more pertinent. In the early days of the modern period, before high-intensity use, the default of ownership fell on the landowner who had a well on his/her land, supported by early doctrines indicating that all resources, including percolating water (i.e., groundwater) on the land belonged to the landowner. Anticipating or reacting to increasing problems of groundwater overexploitation, a common trend over a period from the 1960s and strongly in the 1990s has been to vest ownership–or other equivalent legal status–of groundwater resources in the government of states on behalf of the people and in the long-term public interest of equity and sustainability.[1] The customary private ownership right was replaced by user-type rights granted and regulated by the government in the form of permit (license, authorization, or concession) systems.

While it did not prevent over-depletion as such, this transition was generally smooth in most countries. The successful functioning of the permit systems generally depends on proper knowledge of the groundwater resources, the willingness of rightsholders to comply with the granted user rights, and the efficient and effective enforcement of this regulation. In developing countries, such enforcement is limited by the weak capacity (and often political sensitivities) of the governments and the perception of the unfairness of the measures. Going toward an effective integrated local water resource management is thus key in such enforcement and, in high maturity settings, a possible contribution to reducing groundwater depletion.

However, not all governments followed this path, with Chile, India, Pakistan, and the U.S. state of Texas being cases in point due to their high dependence on groundwater. With private ownership of groundwater (also termed the rule of capture in Texas) still prevailing as a legal right, the continuing challenge for these countries is to identify measures that guide and support groundwater management and protection through broader water and land use management plans, groundwater conservation areas, monitoring and information on groundwater status, education, and the promotion of conservation and supply side technologies, especially managed aquifer recharge. Finally, the support for and encouragement of local-level self-management, which speaks to the solidarity of stakeholders and local action, is a common ground for possible avenues in these contexts.[2]

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1. Burchi and Nanni 2003.
2. One example of a program adopting this approach is the India National Groundwater Management Improvement Program, or Atal Bhujal Yojana (ABHY), which is supported by the World Bank. It seeks to reposition water users at the center of efforts to replenish groundwater. The US$900 million program, of which half is a loan from IBRD, will be implemented between 2020–2025 and aims to strengthen the institutional framework for participatory groundwater management in seven states (Haryana, Gujarat, Rajasthan, Karnataka, Madhya Pradesh, Maharashtra, and Uttar Pradesh). By engaging in regular water budgeting exercises at the village level and in designing participatory water security plans, community members not only have a say in how groundwater is managed but, moreover, become increasingly aware and informed of the variation of the water table and are incentivized to change their own behavior in how they consume water.

B

Groundwater underpins the development of agriculture, cities, and critical ecosystems

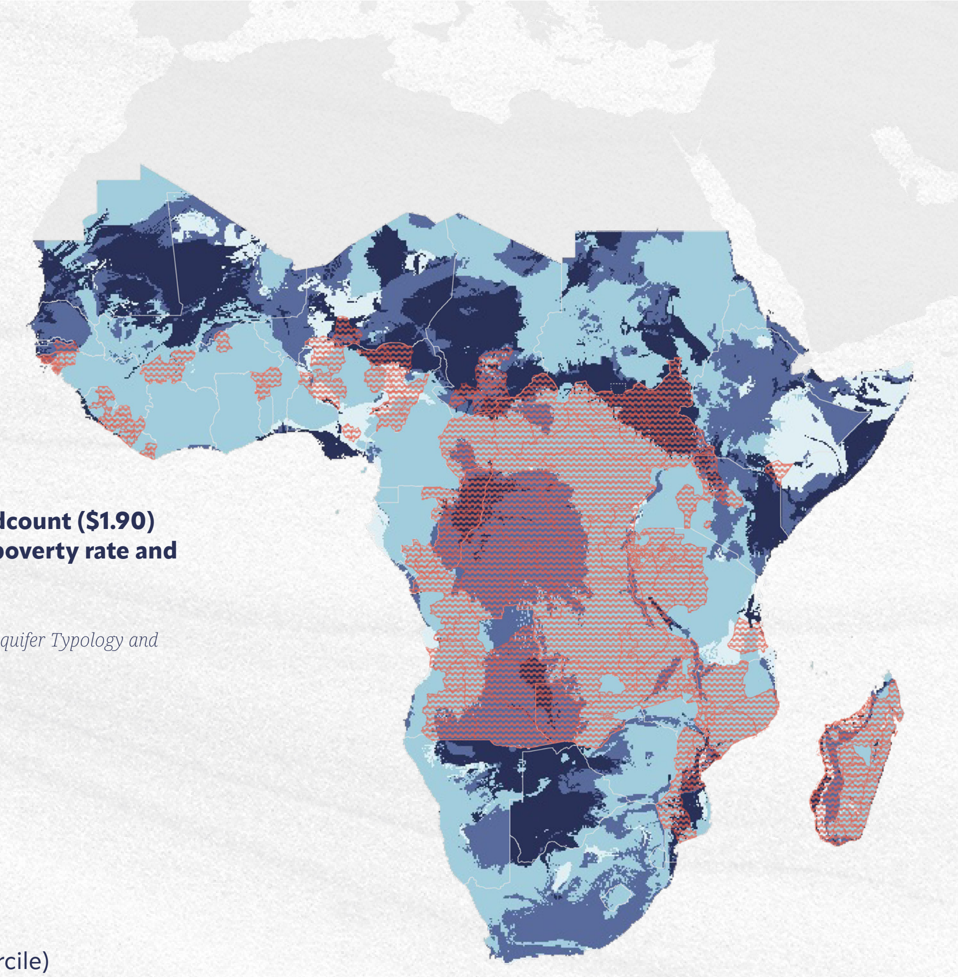
Food security

What groundwater lacks in visibility, it makes up for in value, and nowhere is this value more visible than in agriculture, where it's been shaping destiny. Groundwater was one of the core ingredients of what the Nobel Prize-winning economist Angus Deaton calls the "great escape" from scarcity.[17] Vast quantities of groundwater have sustained the intensification of agriculture brought on by the Green Revolution in various regions of the world. Millions of farmers depend on groundwater irrigation to help produce 40 percent of the world's crops, including a large proportion of staple crops like rice and wheat.[18] In South Asia, the rapid rise in groundwater-based irrigation since the 1960s has been driven primarily by atomistic or personal irrigation systems that eclipsed an earlier era dominated by centralized surface irrigation projects.[19] In India, groundwater-based irrigation directly sustains up to 20 percent of cropping intensity,[20] 28 percent of the total annual irrigated crop production, and more than half of dry season irrigated crop production.[21] And in the arid and semiarid areas of the Middle East, groundwater has been the backbone of water and food security. Overall, groundwater has supported the upward trends in yields and productivity—success that also underplays the fact that a significant proportion of the groundwater to achieve this gain has been through an unsecured loan (of groundwater) from future generations.

Well managed, the resource can provide food security for many more—particularly in Sub-Saharan Africa. Local shallow aquifers in the region hold 61 percent of the groundwater available but are largely untapped, with only 7 percent of the total cultivated area of 183 million hectares now irrigated. Although an estimated 40 million hectares could be suitable for irrigation from this water source, it is used for only 12.8 million hectares, and most of the irrigated land is in five countries only: Mauritius, Madagascar, Sudan, Ethiopia, and South Africa. In Sub-Saharan Africa, one of the key assets to increase irrigation is groundwater, however more so at a small scale with the growing affordability of technologies such as solar pumps.[22] Existing evidence hints at the potential of groundwater irrigation for food security but mostly ignores the groundwater endowment in protecting household nutrition. In rural Benin, solar-powered drip irrigation systems installed in communal gardens increased the consumption of vegetables among program beneficiaries during the dry season, and irrigators were 17 percent less likely to feel chronically food insecure one year after the project started.[23]

Existing estimates project that a 120-fold increase (by 13.5 million hectares) of groundwater irrigation is likely possible, even when looking at only 13 countries in Sub-Saharan Africa.[24] While more work is needed to refine those estimates and to provide some insights on the phase-in of possible investment to promote farmer-led irrigation at scale, such results hint at the potential an expansion of groundwater irrigation could do to improve the livelihoods of about 40 percent of the rural population in some of the world's poorest countries. Most promising for farmer-led irrigation are local shallow aquifers, given their ease of access, limited concerns for their overexploitation, and potential for weathering inter-seasonal variations.

In Sub-Saharan Africa, more than 255 million people living in poverty ($1.90 line) reside in areas where the expansion of shallow groundwater is feasible and could reduce poverty by protecting people from climate shocks (map 1.1). In West Africa, close to 40 million people suffer from acute food insecurity—brought on by the very large annual variability in the shocks to rainfed crop and livestock yields. That puts rural livelihoods at the mercy of the vagaries of weather and now of climate change. Irrigation can also extend the agricultural season through dual-crop farming in a calendar year and thus lessen seasonal deprivations and adapt to climate change. For the G5 Sahel (Burkina Faso, Chad, Mali, Mauritania, and Niger), the World Bank estimates that by 2050, with no adaptation policies and investments, the poverty rate would increase from 27 percent in the medium-growth baseline (no climate change) to 29 percent in the wet and optimistic climate scenario and to 34 percent in the dry and pessimistic climate scenarios.[25] In those five countries, 62 percent of groundwater is in local shallow aquifers.



Map 1.1

Subnational poverty headcount ($1.90) with top tercile regional poverty rate and aquifer typology

Source: World Bank Groundwater Aquifer Typology and World Bank poverty data.

Aquifer typology

○ Karstic
● Local/Shallow
● Complex
● Major alluvial

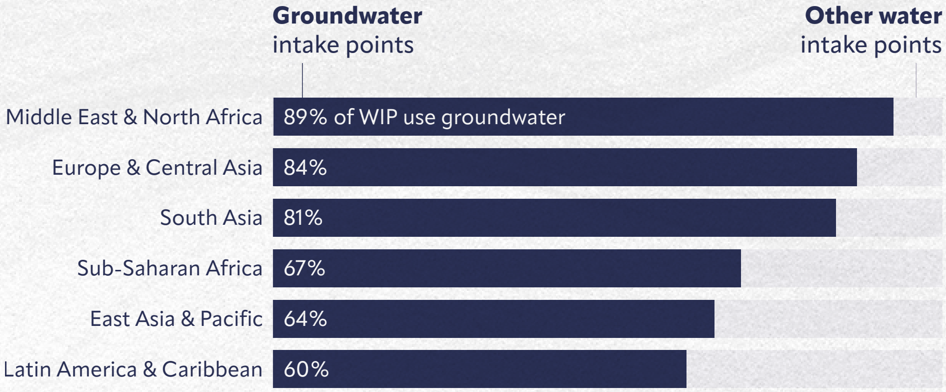
▨ Subnational Poverty Headcount > 58 (top tercile)

Urban services

Although seldom recognized, groundwater also sustains the growth of cities, and most large cities in developing countries rely on groundwater as one of their main sources of water (see Annex 4). In most developing countries, groundwater represents 60 to 90 percent of water intake points (figure 1.3). Groundwater has some key advantages for the provision of water for domestic purposes, assets that are even more valuable in developing countries. First, decentralized groundwater sources can facilitate access in more recently developed areas of growing cities where network access is not available. Second, its natural quality is typically high—if geogenic and anthropogenic contamination is not a concern. Third, large aquifers have a large capacity effect, helping to manage demand and buffering against dry shocks.

In Africa, access to shallow groundwater facilitates urbanization, itself a driver of poverty reduction. More than half of Africa's population is expected to live in cities by 2040. Indeed, given the absence of infrastructure to provide water in urban and peri-urban areas, easier economic access to groundwater, such as local shallow aquifers, can lead households to self-supply through private wells. And the use of such private wells has ballooned with urbanization in Latin America, South Asia, and Sub-Saharan Africa. The presence of such aquifer facilitates the installation of new and often poorer households in urban areas and are often an improvement over the rural access previously enjoyed. But the haphazard multiplication of those private wells can risk contamination without a corresponding expansion of sanitation infrastructure and urban waste management, particularly exacerbated in the event of floods. And once drilled and operating, private wells may constitute obstacles to the expansion of utility services, even when water supplied at the cheaper social tariff would be controlled and of better quality.

Figure 1.3
Reliance on groundwater intake for drinking water source



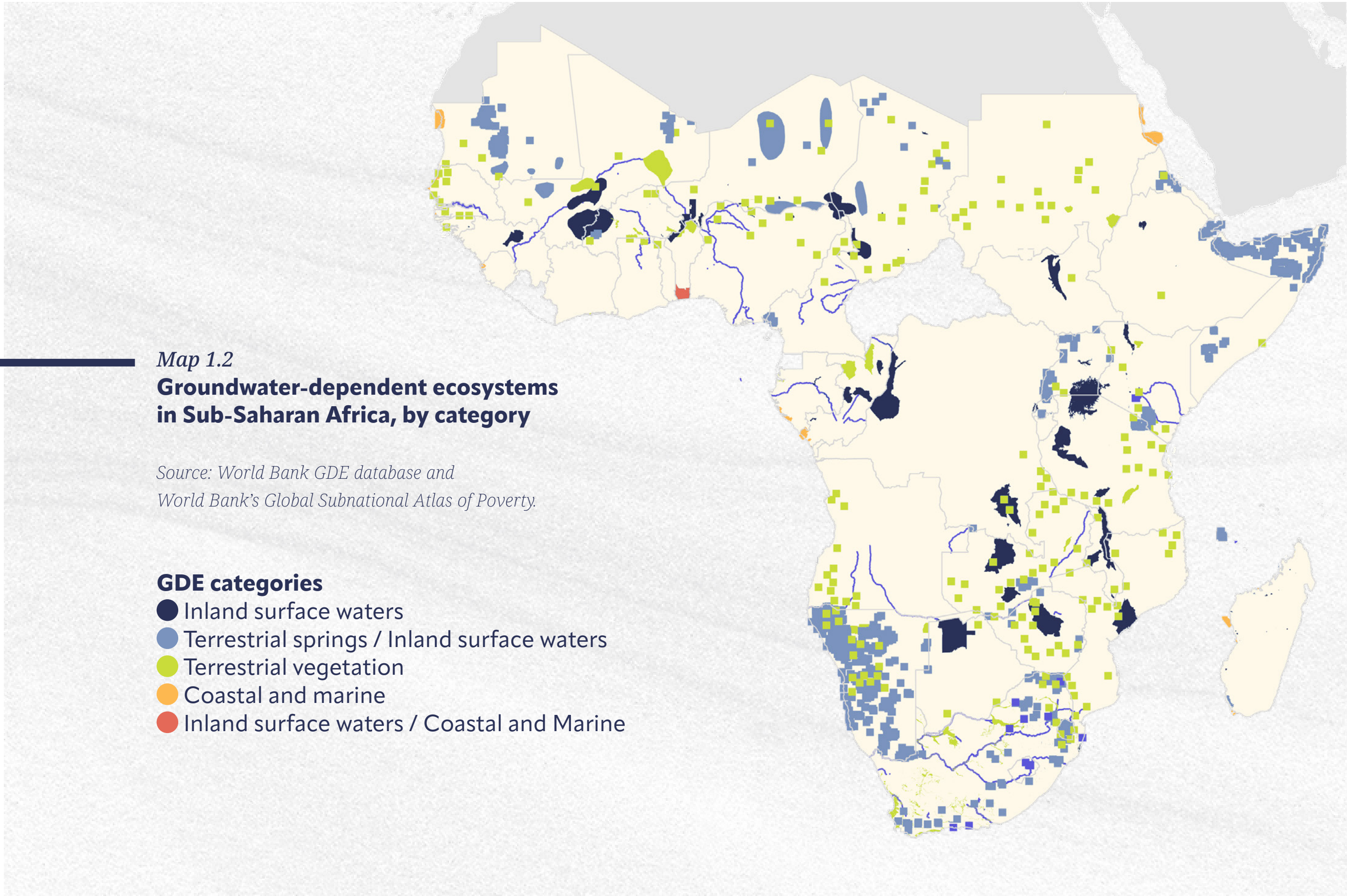
Source: World Bank calculation using data on urban water intake points from The Nature Conservancy and McDonald (2016).

Note: The calculation covers 220 cities from non-high-income countries: 19 from low-income, 111 from lower-middle-income, and 90 from upper-middle-income countries. The non-high-income countries were identified by the World Bank income classifications set on July 1, 2022. The percentage values were calculated by city and then averaged across cities in each region.

Groundwater-dependent ecosystems

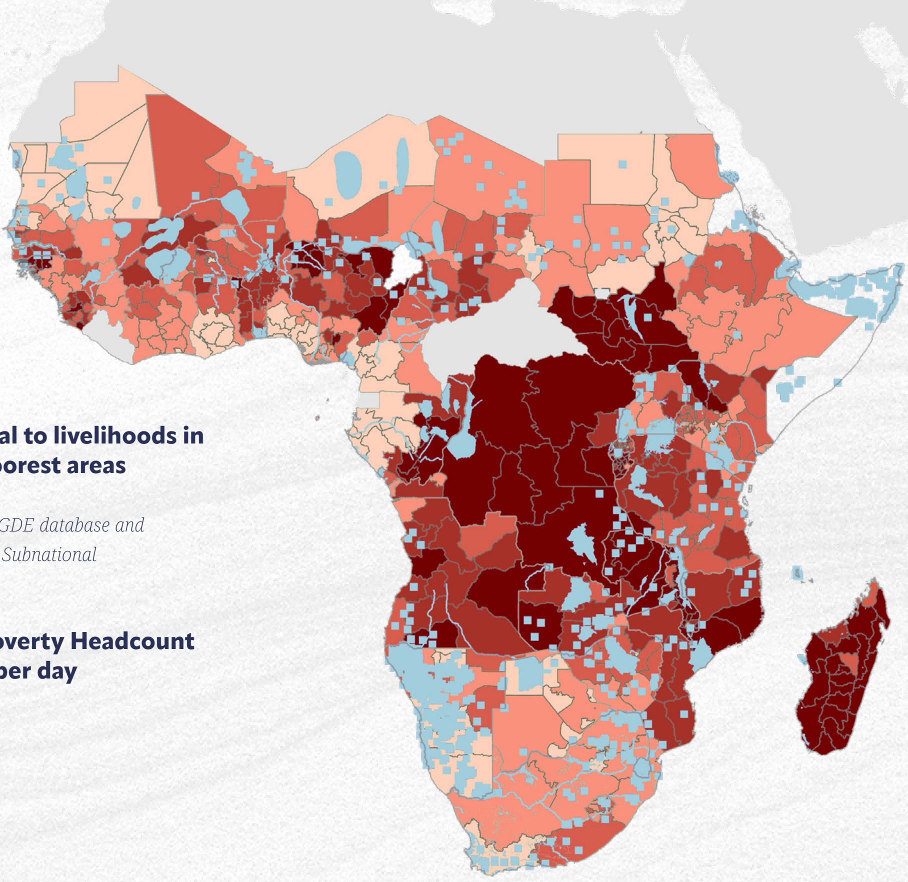
Less visible but equally critical, groundwater also sustains a broad range of ecosystems critical to livelihoods. Groundwater-dependent ecosystems (GDEs) require access to groundwater on a permanent or intermittent basis to meet all or some of the water requirements to maintain plants and animals, their ecological processes, and their ecosystem services (see Annex 3). The importance of GDEs has been increasingly recognized over the past decade, helped in part by the broader discussion around climate change and the recognition of the net carbon sink role of GDEs.[26] GDEs also support the livelihoods of some of the most vulnerable Sub-Saharan populations, sometimes in hidden ways, such as for pastoralists in the Sahel through the hydraulic lift of some trees.[27] Still, GDEs are not systematically identified and mapped at scale, particularly in developing countries. This lack of information is problematic since GDEs, particularly in dryland areas, are most exposed to small variations in the groundwater that can threaten their existence.

A new World Bank database of GDEs in Sub-Saharan Africa shows their diversity—and their importance to people living in poverty. Compiled using a wide range of sources reflecting local and academic knowledge, the database identified more than 200 GDEs across four main geographic types—inland surface waters, coastal and marine ecosystems, oases and springs, and terrestrial vegetation (map 1.2). This new database helps bring GDEs into focus but will require further expansion and refinement to reflect all GDEs in the region better and contribute to their monitoring and protection (box 1.1). GDEs are in areas of high vulnerability to poverty, providing key socioeconomic services in addition to their critical role in broader ecosystems (map 1.3).



Map 1.2
Groundwater-dependent ecosystems in Sub-Saharan Africa, by category

Source: World Bank GDE database and World Bank's Global Subnational Atlas of Poverty.



Map 1.3
GDEs are critical to livelihoods in some of the poorest areas

Source: World Bank GDE database and World Bank's Global Subnational Atlas of Poverty.

C

Groundwater's climate buffering is nature's multi-risk insurance

Increased variability of water can weigh heavily on communities and is one of the most significant sources of risk facing communities in developing countries. Adapting to rainfall variability is often much more challenging than accommodating long-term trends because of the unpredictable duration and uncertain magnitude[28]. Not surprisingly, most countries have listed water as the priority for adaptation in their climate change plans. The latest IPCC report also finds that most climate change adaptation strategies target agriculture, which accounts for 70 percent of global water consumption. One of the most ubiquitous adaptation strategies is irrigation, the strategic storage and water application on crops. These efforts can play a crucial buffer role in shielding crops from some of the hardships and uncertainties arising from the increased variability of rainfall and increased heat.[29]

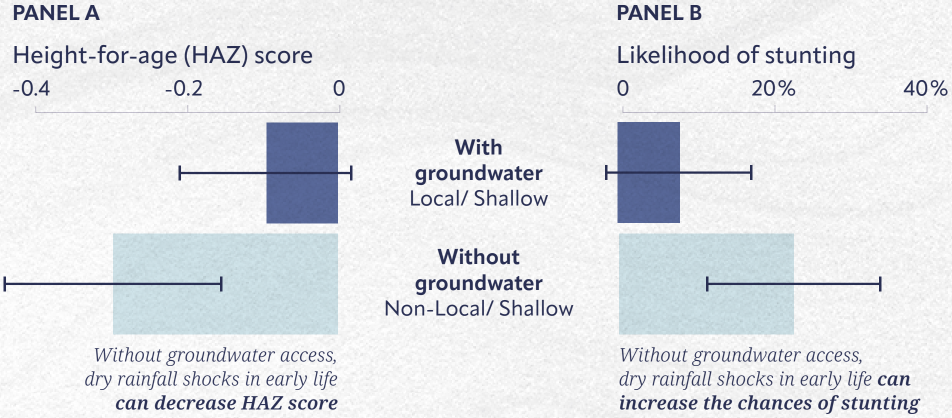
Groundwater buffers against droughts because it can provide access to fresh water when surface water resources are scarce. Empirical studies in South Asia confirm that climatic variability increases groundwater utilization.[30] Use of the resource can be of particular importance in areas like Sub-Saharan Africa that are highly vulnerable to climatic shocks. In 2022 alone, drought conditions in eastern Ethiopia, northern Kenya, and Somalia led the UN to warn that some 22 million people could risk starvation. In Somalia, the rainfall in the March to May season was the lowest in the past six decades. And large parts of DR Congo and Uganda have also experienced very dry conditions compared with the average.[31] To what extent can groundwater cushion such shocks, protect agricultural productivity, and ensure food security in Sub-Saharan Africa?

New analyses for this report show that individually accessible, sustainable shallow groundwater has the potential to insulate agriculture from the adverse effects of rainfall variability—protecting food security and human capital (see Annex 7). Without such a natural buffer provided by local shallow aquifers, households could suffer almost twice the loss in agricultural productivity. This, in turn, has ramifications for food security and the health outcomes of children. Droughts can alter household income and nutritional intake, with important consequences for physical and cognitive development. Stunting is widespread in Sub-Saharan Africa. More than 35 percent of children under the age of five are considered stunted (more than two standard deviations below the reference height-for-age of their cohort). Children who experience a large dry shock in infancy are more likely to be stunted, which in turn can lead to long-term health impacts that stretch well into adulthood.[32] Disturbingly, women who experience a large dry shock in infancy are also 29 percent more likely to have a child suffering from some form of anthropometric failure.[33]

To what extent can shallow groundwater insulate against such early-life shocks? Analysis for this report—using a spatially disaggregated health database of 687,652 children across 32 countries in Africa spanning 15 years—finds that while rainfall shocks experienced in a child's earliest years can decrease height-for-age (HAZ) scores and increase the likelihood of stunting, access to shallow groundwater has the potential to buffer against such harmful impacts (figure 1.4). Indeed, the results show that without such access, greater exposure to droughts in early childhood, on average, decreases the HAZ score (Panel A, Figure 1.4) and raises the chances of stunting by up to 20 percent[34] (Panel B, Figure 1.4). Thus, by insulating farms and incomes from shocks, the insurance of shallow groundwater translates into protection against malnutrition, particularly for children under the age of 5. These findings highlight the urgency of boosting sustainable access to local shallow aquifers in Sub-Saharan Africa. Doing so can shape the destinies of millions of children, which is critical for the future development of Africa. Access to shallow groundwater can also boost the benefits of small-scale irrigation. Evidence suggests that small-scale irrigation can help to address local nutrient deficiencies and improve dietary diversity, contributing to the resilience of smallholder producers.[35]

Cities can also benefit from the natural buffer that groundwater affords: the impact of day-zero-type events on city growth is negligible when they can rely on well-managed groundwater as part of their water source portfolio. Recent headlines from Chennai, India; São Paulo, Brazil; and Cape Town, South Africa, show that some of the world's megacities are beginning to face day-zero events, where water supplies threaten to dry up. As the challenge mounts to absorb the growing demands of urban populations and as shocks to water supplies increase, city planners increasingly need to rethink urban planning to ensure that cities remain engines of economic growth. Groundwater could ensure such a future. Recent analyses suggest that groundwater may have protective effects on cities, buffering their economic growth from the effects of day-zero type of events.[36]

Figure 1.4
Malnutrition and the role of shallow groundwater in Sub-Saharan Africa

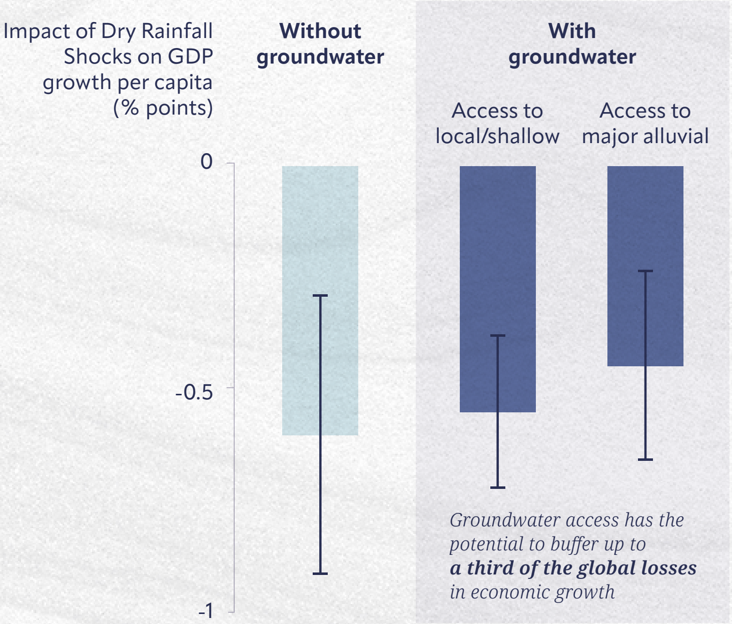


Together, groundwater's effects on farms, cities, and families cascade into overall effects on economic growth—with easily accessible aquifers buffering up to a third of the global losses in economic growth in the event of a drought. During drought years, local shallow and major alluvial aquifers that are readily accessible to individuals provide a natural insurance policy and have the potential to buffer up to a third of the global losses in economic growth, with the largest buffering effects seen in areas dominated by major alluvial aquifers (figure 1.5).[37] This numerical result corroborates with known differences in aquifer systems. While major alluvial aquifers are vast, often regional, groundwater tanks with large buffer capacity that can overcome multiyear climatic shocks, local shallow aquifers depend primarily on seasonal recharge and can overcome interannual climatic shocks.

In sum, the benefits are enormous. Groundwater can play a critical role in adaptation to climate change, but only if action is taken to protect it. As groundwater becomes depleted and extraction is more constrained, the resilience it bestows may diminish. Without action, we risk increasing our vulnerability to climatic shocks, leaving groundwater users and ecosystems high and dry. The next chapter delves deeper into these challenges.

Figure 1.5

Groundwater is key to protecting economic growth



Groundwater access has the potential to buffer up to ***a third of the global losses*** *in economic growth*

Box 1.3

When the hidden wealth is shared across borders: Transboundary aquifers

For most human history, groundwater has been perceived as a local resource. But rapid and uncontrolled groundwater exploitation and pollution over the last decades have shown the importance of examining groundwater problems and solutions at regional and, increasingly, global scales. Groundwater—and externalities originating from its use—often cross-national borders, flowing within transboundary aquifers. Borders over these aquifers make their coordinated management and development more complex.

The International Groundwater Resources Assessment Centre (IGRAC) has identified at least 468 transboundary aquifers: 106 of these are in Africa, 135 in the Americas, 130 in Asia (including Central Asia) and Oceania, and 97 in Europe.[1] In Africa, transboundary aquifers underlie 40 percent of the continent where 33 percent of the population lives, often in arid or semi-arid areas.[2] The exact identification and delineation of many transboundary aquifers is still incomplete, particularly at the local level where transboundary aquifers may be small but still key for livelihoods.[3] The number of identified transboundary aquifers has been increasing steadily since the first Transboundary Aquifers of the World Map was released in 2009.[4]

Transboundary aquifers are particularly important in arid and semi-arid regions, where groundwater serves as the primary source of water for human and environmental sustenance. Regions with high dependence on transboundary aquifers include the Sahara (Northwestern Sahara Aquifer System, Nubian Sandstone Aquifer System), the Middle East (Mountain Aquifer, Umm Er Radhuma aquifer), South Asia (Indo-Gangetic basin), South America (Guarani) and areas along the United States and Mexico border (Lower Colorado, Hueco Bolson aquifers, among others). While economic dependence on these transboundary aquifers has not been quantified, assessments suggest that many of these aquifers are being depleted, with depletion rates showing significant acceleration since the turn of the century.[5] Hotspots of transboundary groundwater depletion include the Indus River Plain (India, Pakistan), the Nubian Sandstone (North Africa), the Umm Er Radhuma aquifer (Arabian Peninsula), and aquifers located along the USA–Mexico border.[6] As pressure on these systems grows, conflicts over their use and management might arise. Already, around the world, transboundary aquifers underlie 40 percent of countries affected by conflict.

1. IGRAC 2021. For an interactive map of transboundary aquifers, visit https://ggis.un-igrac.org/view/tba.
2. Nijsten et al. 2018.
3. Fraser et al. 2020.
4. IGRAC 2009.
5. Wada and Heinrich 2013.
6. Wada and Heinrich 2013.
7. Sadoff et al. 2017.

Most nations exploit groundwater from transboundary aquifers unilaterally without knowing the cross-border implications or even that the aquifer is transboundary. In fragile contexts and those with legacies of significant tensions over natural resources, transboundary water cooperation can act as an important approach to deescalate tensions, promote stability, and build resilience to shocks that might otherwise act as a trigger for conflict.[7]

To date, only six treaties targeting specific transboundary aquifers have been ratified compared to hundreds for transboundary rivers and lakes. As pressure on these systems grows, more attention needs to be devoted to fostering cooperation on shared groundwater. In this respect, the 2008 Draft Articles on the Law of Transboundary Aquifers prepared by the International Law Commission and the 2009 General Assembly Resolution A/RES/63/124 encouraged countries to make appropriate bilateral and regional arrangements for the proper management of their transboundary aquifers using these Draft Articles as guidance represent important milestones. Additionally, both global water conventions, the 1992 Convention on the Protection and Use of Transboundary Watercourses and International Lakes and the 1997 Convention on the Non-navigational Uses of International Watercourses, also cover transboundary groundwater resources, with the former covering all transboundary aquifers even when not associated to an international watercourse and the latter covering alluvial aquifers only.

Source: Background paper for this report by Borgomeo (2023).

2

Staying solvent—avoiding bankruptcy

Managing depletion, degradation, and competition

A

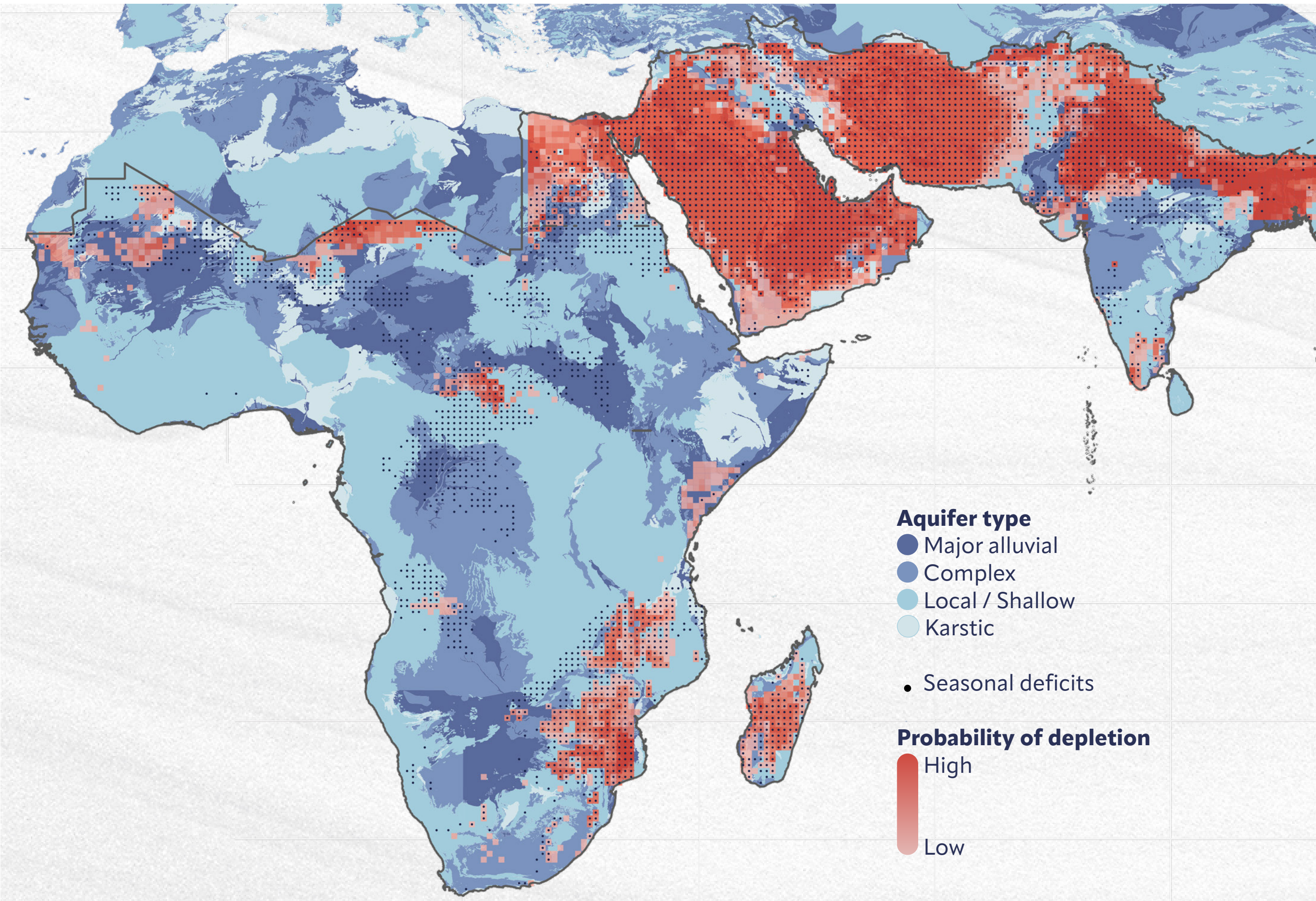
Depletion: Drawing down reserves, draining wealth

Groundwater levels are being depleted at alarming rates in the world's arid and semi-arid regions, with the effects most visible in the Middle East and South Asia. In Iran, where groundwater extraction dates back at least two and a half millennia, but with a typical escalation in the 1960s and 1970s, the situation is dire. More than three-quarters of the land is under extreme groundwater overdraft —over-abstracted volumes between 1965 and 2019 have cumulated to ~133 km^3, a loss that is about 3.4 times the capacity of the Three Gorges Dam, the world's largest hydropower project.[38] Not too far away, in India, groundwater use exploded by 500 percent over the past 50 years, making it the world's largest guzzler of groundwater.[39] These trends have contributed to rapid declines in groundwater levels, especially in the northwestern states where the Green Revolution took off. Estimates suggest that over-abstracted volumes reached 122 to 199 km^3 between 1996 and 2016 alone.

In its simplest terms, groundwater depletion refers to a sustained multiyear decline of the water table, resulting from withdrawals that exceed average available groundwater resources. It results from groundwater mining and denotes a situation of unsustainable withdrawal. This slow-moving phenomenon of depletion is thus distinct from transient fluctuations in groundwater levels. While detectable across most aquifer typologies, sustained long-term water level trends don't occur in local shallow aquifers that deplete and replete seasonally. Here, instead, groundwater stress can manifest as increasing variability in seasonal depletion that impacts the short-term availability of the resource. Depletion, both seasonal (increasing volatility of the water table) and long-term (multiyear decline of the water table), can cause groundwater stress. It is usually accompanied by a reduction in the yield of boreholes and water wells and even their complete drying up or failure. Ultimately, users face less volume and higher costs of extraction, in effect, a loss in returns from investment in the resource. Since groundwater remains a crucial asset, its depletion can reduce economic welfare by depreciating its natural capital. A recent valuation exercise applied to the Kansas High Plains' groundwater aquifer revealed that Kansas lost approximately $110 million per year of the state's total wealth held in groundwater between 1996 and 2005 due to the depletion of its groundwater supply.[40]

Perhaps more critically, depletion decreases the buffering capacity of the impacted aquifers leaving less water available for when it is most needed as regions face increasing temperatures and more variable precipitation and aquifer recharge because of climate change. As reliance on groundwater grows even as access to supplies dwindles, the impacts of drought and heat on water users could be greater in the future than today. Paradoxically, the groundwater resource that has cushioned climatic variability in the past may fail to continue attenuating its adverse impacts in the future.

To get a glimpse of the changes in groundwater storage globally, we make use of the Gravity Recovery and Climate Experiment (GRACE) satellites that have extensively been used for monitoring depletion. Using downscaled satellite data from April 2002 to December 2020, Figure 2.1 highlights hotspots based on the two groundwater stress indicators used in this analysis—declining trends and seasonal deficit (figure 2.1 and box 2.1). We find significant groundwater stress hotspots in the Indo-Gangetic basin, Iran, the Arabian Peninsula, and parts of Southern Africa. Moreover, up to 92 percent of transboundary aquifers in the study region show signs of dwindling groundwater storage.



Map 2.1

Declining trends and seasonal groundwater deficits using downscaled GRACE satellite data

Source: Downscaled Gravity Recovery and Climate Experiment (GRACE)-observed groundwater storage (GWS) estimates prepared for the report (Chen et al., 2023).

Notes: GRACE satellite data used extensively for monitoring depletion are downscaled at a granular scale to understand global changes in groundwater storage. Using downscaled satellite data from April 2002 to December 2020, the map highlights hotspots based on the two groundwater stress indicators used in this analysis—declining trends and seasonal deficit. The confidence of estimated negative trends in GRACE-derived GWS is based on nine potential realizations of GRACE (CSR, JPL Mascons, GFSC) products and LSMs (CLM, Noah). The high to low gradation in the probability of depletion refers to the number of GRACE GWS realizations where a particular grid cell showed negative significant (p-value<0.05) trends.

Box 2.1

Eye in the sky: using satellite data to measure groundwater storage changes

The Gravity Recovery and Climate Experiment (GRACE) satellites have provided a revolutionary way for monitoring groundwater storage changes at a global scale and filling knowledge gaps, especially in data-scarce regions. GRACE data capture changes in terrestrial water storage (TWS), which is an aggregate of changes in snow, surface water, soil moisture, and groundwater. The groundwater storage (GWS) signal can be isolated by subtracting non-groundwater components. The base units are "centimeters of equivalent water thickness," which represents a change in gravity caused by a change in the height (centimeters) of water spread out over a given area.

However, the spatial resolution of GRACE (~90,000 km^2; 3° x 3°) limits its ability to inform management decisions at a finer regional scale. To overcome these spatial limitations, a machine-learning (Random Forest) approach was used to downscale the spatial resolution of GRACE-groundwater estimates from 3° resolution to 0.5° resolution for the report (Chen et al., 2023). The downscaling approach involved, first, training Random-Forest models at a 3° resolution to establish the relationship between GRACE-measured TWS and predictor variables such as precipitation, evapotranspiration, and runoff. The trained model was then applied at the target resolution using predictor variable data at a 0.5° resolution. Last, the GWS signal was isolated from the downscaled GRACE-TWS by subtracting non-groundwater components (like snow, surface water, and soil moisture). This downscaling approach was used to estimate monthly changes in groundwater storage at a 0.5° resolution for the study region, which included Sub-Saharan Africa, the Middle East, and South Asia from 2003–2021.

Interpretation of GRACE data has mostly relied on the use of trends to understand changes in groundwater storage at a given location.[1] Areas in red highlight regions with significant (p-value<0.05) negative trends in GWS between 2003–2020. For this analysis, we perform trend estimates over multiple models using a combination of TWS solutions and land-surface model (LSM) estimates. The high to low gradation in certainty refers to the number of models for which the GWS time-series showed significant negative trends for a particular grid cell. Since long-term water level trends mostly capture stress in major alluvial aquifers, we also use the GRACE data to measure increasing seasonal variability in storage to capture groundwater storage change across local shallow aquifers systems.[2] The dotted areas depict the Deficit 10/20 stress indicator highlighting areas that experienced short-term stress and pronounced groundwater storage deficit periods between 2010–2020.[3]

Details regarding the construction of the indicators are provided in Annex 7.

[1] Asoka et al. 2017; Shamsudduha and Taylor 2020.
[2] Fishman et al. 2011; Hora et al. 2019.
[3] Thomas et al. 2014, 2017.

Nearly 24 to 38 percent of areas underlaid by local shallow and major alluvial aquifers that provide promising buffering benefits for Sub-Saharan Africa, the Middle East, and South Asia show some signs of stress. As explained in Chapter 1, groundwater plays a crucial buffer role in shielding farms, cities, and families from some of the hardships and uncertainties arising from the increased rainfall variability and heat. The benefits have no doubt been enormous. But the depletion seen in many of the same regions most dependent on groundwater has spurred concerns about the socio-economic consequences and the possibility that it may arrest progress in economic development and poverty alleviation. Not surprisingly, most of these depleted areas occur in areas underlaid by major alluvial aquifers where long-term declines in water tables are possible. But other metrics of stress, such as increased volatility in the water table are also seen across other aquifer systems. To investigate whether the buffering abilities of groundwater are changing over time, the analysis expands on chapter 1 and measures the modulating effect of local shallow and major alluvial aquifers on economic growth during drought events across eight-year periods from the early 1990s to the mid-2000s.

Over time, the buffering benefits of groundwater are dissipating, with most of the impact driven by areas underlaid by major alluvial aquifers that have experienced increasing declines in groundwater storage. These results corroborate country-specific analysis in India that shows that groundwater played a buffer role against droughts and dry shocks up to the mid-1990s, providing a 10–20 percent agricultural revenue advantage, which then disappears after 1995 possibly due to lowering of groundwater tables.[41] In sum, the results suggest that depletion makes it harder to exploit the full potential of groundwater. Uncertainty induced by climate change will only add to this vulnerability as sustainable groundwater irrigation in the future becomes less feasible.[42]

The consequences of depletion are far-reaching—severely reducing farm output, either when output is measured directly or, in a few cases, when embodied in land values. In India, cropping intensity can decline by up to 20 percent.[43] Food grain production can decline by 8 percent in response to a 1-meter decline in the water table from its long-term mean.[44] And a one-standard-deviation reduction in the depth of the water table can result in a loss of profit amounting to 13 percent of the value of output, or 14 percent of annual household income.[45] More depleted areas can also face declines in land values or in lease prices.[46] And groundwater depletion can increase poverty.[47] In areas where water tables are lower, poverty rates are 10-12 percent higher than where groundwater is more easily accessible. This provides strong evidence against the idea that equitable adaptation possibilities are sufficiently available to fully mitigate the impacts of depletion.[48]

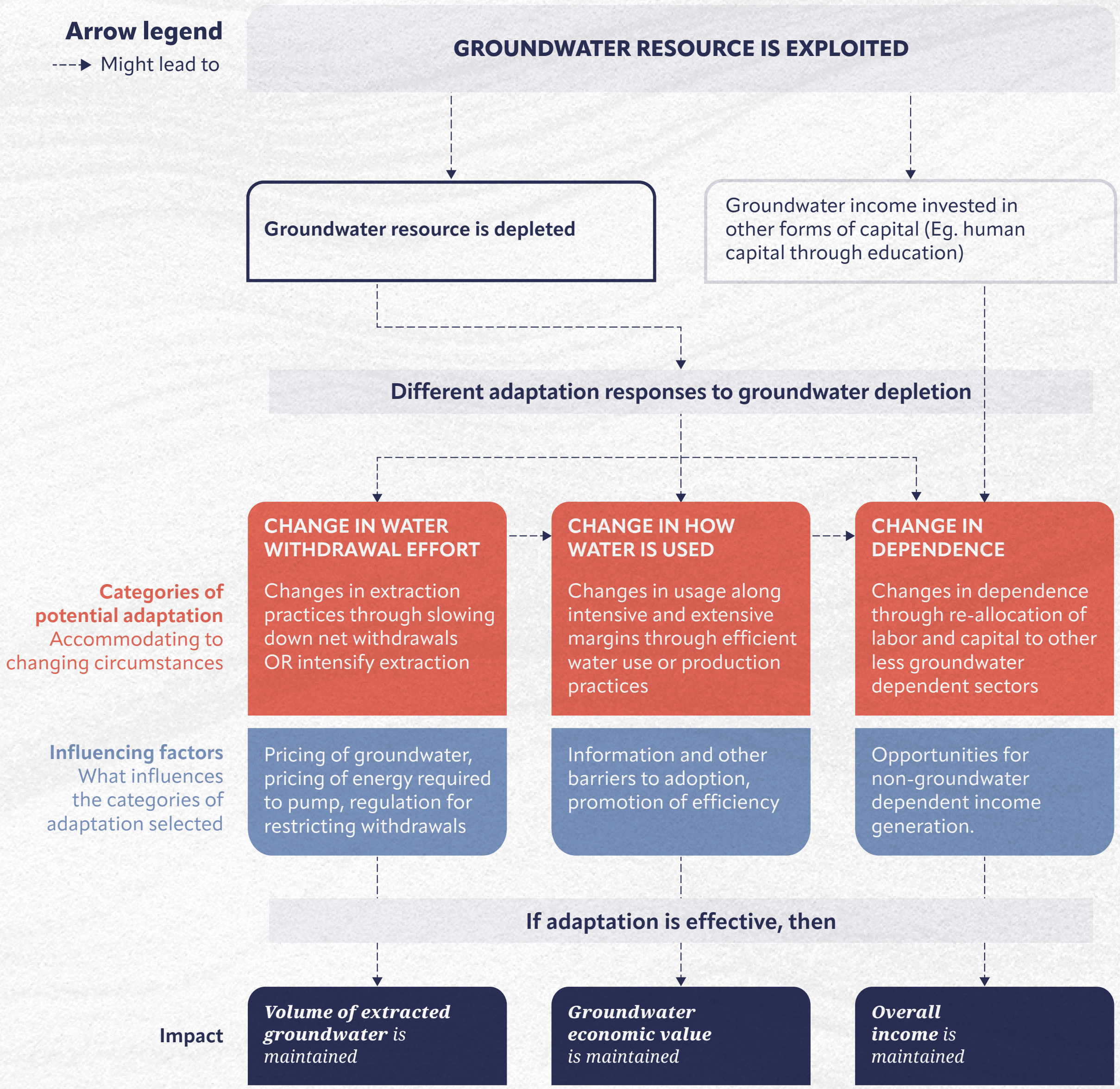
How do users cope with such depletion? They adopt three main strategies to cope with depletion: change withdrawals, change use, and change dependence on the groundwater resource (figure 2.1).[49]

Depletion mostly, but not always, leads to increases rather than reductions in extraction effort—such as drilling deeper wells. In Iran, the operating times of water wells have increased by 17 percent, indicating an intentional effort to increase groundwater withdrawals.[50] But this form of response varies greatly across the world. Perhaps the largest study of the responses to depletion, Jasechko and Perrone (2021)—analyzing 39 million wells from 40 countries—finds that as groundwater tables are falling in many areas, wells become deeper over time, but this is not the case in many other areas. Indeed, in some parts of semi-arid India, man-made water harvesting structures have served as an adaptation to groundwater depletion.[51] And they are said to have conserved the resource to a significant extent through collective action at the community level and later with government support.[52]

As depletion leads to deeper wells, socioeconomic inequalities also deepen. Where the evidence is quite clear, however, is that where drilling takes place, depletion exacerbates socioeconomic inequalities in affected populations. Why? Mainly because the better off can deepen their wells and "chase the water table," while others lose access to the resource or experience intermittent or permanent well failure.[53] This dynamic is documented in multiple studies in India,[54] North Africa,[55] China,[56] Mexico,[57] and even in high-income countries.[58] So, the poor and the marginalized must often resort to other coping mechanisms, like buying water, cultivating less profitable crops, or even leasing or selling their land (box 2.2).[59] Women and girls living in rural areas bear an added burden from this groundwater insecurity due to the responsibilities for water collection they assume in many countries.

Figure 2.1

A conceptual framework for adaptation responses to depletion



Source: Background paper for this report by Fishman and Zaveri (2023).

Box 2.2

What happens when groundwater resources become scarce? Uncovering fault lines with primary data

As groundwater resources become scarcer, how will the equity and efficiency of allocations be affected? Primary data across different geographies reveal that often the poor and marginalized disproportionately suffer the impacts of depletion—overrepresented among these groups are often women.

In three districts in Andhra Pradesh, surveys between 2016 and 2019 reveal that 15 percent of the wells failed between the two surveys, a dramatic rate for a period of three years. Marginalized farmers were more likely to experience such failures. Overall, only 17 percent of those whose wells failed managed to sustain cultivation on their plot. For the others, the share of the cultivated area went down by 70 pp, the likelihood of the plot being left fallow went up by 75 pp, and profits from the plot declined by a staggering 80 percent. There was some suggestive evidence of male labor migration in response to well failures, but overall, no evidence of any effective adaptation.

In Gujarat, where informal groundwater markets are active, surveys show that they are governed more by norms and social contracts than by supply and demand. Water buyers are 30 percent less likely to belong to dominant castes—and have lower education, assets, and income. While all owners sell water to poorer water buyers at socially accepted rates, when water becomes scarcer, these buyers are the first to face reductions in supply. In anticipation of growing future groundwater scarcity, water buyers are also more likely to report reducing cultivation, while well owners are more likely to report deepening wells or drilling new ones. Results in Karnataka are similar. Once a well fails, the poorer are less likely to cope by deepening it or drilling a new one. The result is a collapse of farm income.

Some studies describe a dynamic of "chasing down the water table," which is followed by an abandonment of groundwater-dependent activities. A boom in groundwater exploitation in the Kuchlagh sub-basin of Balochistan, Pakistan, eventually led to rapid depletion. The researchers documented the process and the way local farmers responded over two decades, a uniquely long-term perspective. They did not find any indication of either conflict or institutional adaptation to conserve the resource, or an improvement in water use efficiency. Instead, farmers adapted by drilling deeper, by using water from alternative sources or by transitioning to non-groundwater-dependent income generation activities.

Hardest hit by depleting groundwater levels are often women and girls, who are already tasked with the responsibility of collecting water for household use in most parts of the country, and who will face the toughest burden under increased water insecurity. Aside from the drudgery that walking long distances to collect water from water points entails, the decreasing availability of water sources is likely to have a host of related gendered effects: girls who need to secure water are likely to miss school or dropout altogether; women may be forced to forego engaging in income-generating activities because their time is spent in collecting water; the already lower yields of female farmers will decrease even further under water insecurity.

Source: For India, background papers prepared for this report by Fishman, Gine, Jacoby (2023), Patel et al., (2023), Blakeslee and Fishman (2023); for Pakistan, Van Steenbergen et al. (2015).

User responses to reductions in water withdrawals reflect incentives. Another type of adaptation strategy users may employ when they are forced to face a reduction in water withdrawals is in changing the use of groundwater along extensive or intensive margins using efficient practices. For farming, this would mean either a reduction in the extent of irrigated land or in the amount of irrigation water applied per unit of land. More efficient technologies, such as micro-irrigation, can save water, but the technologies require upfront investments that could place a burden on some water users, despite financial savings over the long term. Even if resources are available to promote investment in water-saving practices and technologies, water savings might not translate into additional groundwater availability because water savings could be reallocated to other uses—an effect known as the Jevons paradox.[60] In many places, the water is not properly valued. Where the use of water does not reflect the true value of the resource and where energy for pumping is subsidized, farmers could be incentivized to expand irrigated acreage rather than save water. While the potential for water-saving technologies to alleviate growing global water stress has been hailed by scientists, economists, and policymakers alike, they alone will not be sufficient to reduce pumping.[61]

If users cannot improve water use efficiency enough to offset the reduction in withdrawals, the reduced withdrawals can reduce output and revenue. This, in turn, may result in other forms of adjustments, such as a reallocation of capital and labor to other less groundwater-dependent sectors. There is less evidence of these "downstream" economic impacts, but some cases suggest migration and shifts of labor to off-farm income-generating activities in response to depletion.[62] Often these opportunities are available only to the wealthy, educated, and more advantaged. If opportunities of this kind are not available to all households, this could lead to a cascade of adverse social and economic impacts, such as drops in consumption, expenditures, and investments in human capital.

Can groundwater depletion be "weakly sustainable"—where the benefits drawn from past use of the depleted resource still yield benefits when it is no longer available? The evidence is cautionary. A well-known idea in the economic theory of the use of natural resources is weak sustainability, which entails the maintenance of income even while the resources on which production was initially dependent become depleted.[63] This is achieved by re-investing rents from the use of the resource in other forms of man-made capital that facilitate a shift to other production systems once the resource is exhausted.[64] For groundwater, weak sustainability might be achieved if the rents from groundwater exploitation are invested in forms of capital that allow users to diversify income generation away from groundwater-dependent activities and thus maintain incomes even as the resource is exhausted. Such investments can be at the levels of national or local government or by users directly and could enable effective adaptation of livelihoods. However, there remains sparse evidence and no clear indications of these dynamics across regions. In several countries in the Middle East and North Africa, some claims suggest that the overexploitation of groundwater resources has briefly and unsustainably spurred rural incomes and enabled the long-term education and migration of younger populations.[65] But in countries like India, there is limited evidence that households in more severely groundwater-depleted villages make bigger investments in human capital through the education of their children.[66] Other studies find no indications that improved access to groundwater has resulted in either an increase or a decrease in the pace of local structural transformation, i.e., the movement of labor away from the agricultural sector.[67]

These observations suggest concerns from both food security and economic development perspectives. While it remains unknown with the available evidence whether the depletion of groundwater aquifers is (weakly) sustainable or economically efficient from a broad development point of view, the available evidence does suggest that local adaptation to groundwater depletion cannot be expected to take place "on its own," without external enabling circumstances or interventions, at least in the farm sector. There is limited evidence that farmers can adapt farming to the reductions in water availability, even though proven technologies and practices can substantially improve water use efficiency. There is also limited evidence that farmers make investments that may allow them to smoothly transition out of irrigated cultivation once the resource depletes. If policymakers would like to see affected populations adapt, on or off the farm, they may have to stimulate these kinds of adaptations.

More importantly, the critical functions and services provided by groundwater suggest that depletion's consequences go beyond the impacts on groundwater users. It affects ecosystems and surface-water users because pumping captures water that would otherwise discharge to springs or rivers and support groundwater-dependent ecosystems (box 2.3). For example, declining groundwater also means that rivers can dry up in the dry season when water is most needed because the baseflows from aquifers feed perennial rivers.[68]

Agricultural return flows form another "hidden pathway" between groundwater and surface water resources. When groundwater is pumped for irrigation, a portion becomes runoff and enters the surface water system. These hidden connections between surface water and groundwater systems suggest that surface water users may not realize that the state of the aquifer—which may be upstream of their location—also determines their surface water supply. Analyses for the report reveal that the hidden pathways of groundwater in river basins that intersect with aquifers at risk of depletion in the future are the greatest in South and East Asia.[69] This means that a loss of groundwater resources may have larger spatial consequences than previously realized. Without groundwater, the surface water contributions to irrigation can decrease by up to 20 percent, affecting ~51,000 square kilometers of irrigated areas, some of which are across national borders from the depleted aquifers. [70] Loss of groundwater supply—whether physical or economic—can thus have greater impacts on total water resources than a simple estimate of groundwater extraction might reveal.

Sinking cities reveal that the initially hidden impacts from groundwater over-depletion can then become exponential through land subsidence. While having groundwater part of a city's "water source portfolio" is an undeniable asset, when this asset is not well managed and groundwater is over-abstracted, the dewatering consequences can translate into land subsidence. This situation affects countries and cities around the world, from Mexico[71] to Iran, Vietnam, and Indonesia. Subsidence greater than 4 millimeters a year is considered problematic. In Iran, the land is sinking at a rate of 6 centimeters a year,[72] while Jakarta is sinking faster than any other city in the world, having subsided more than 3.5 meters since the 1980s and continuing to sink at rates up to 20 centimeters a year.[73] The absence of reliable piped water is one of the causes of groundwater overexploitation, as users without piped access resort to unregulated abstraction.[74] Land subsidence in coastal areas also increases the risks of saline intrusion in the aquifer as well as the risk of flooding and sea-level rise, as is observed in the Mekong Delta.[75] The impact of salinization of groundwater and subsidence, partially caused by groundwater depletion, in the Mekong and Red River delta in Vietnam, will result in reducing agriculture contribution to GDP by 1.67 percent by 2035. [76] In Indonesia, Inaction on curbing groundwater over-abstraction is predicted to increase the impact of floods due to land subsidence and reduce GDP by up to 1.42 percent by 2045.[77] Land subsidence threatens 15 of the 20 major coastal cities ranked with the highest flood risk worldwide.[78] While the impacts of sea-level rise have been extensively studied, groundwater-led land subsidence has received limited attention (see Box 2.4), with the main focus on infrastructure, ignoring other costs and impacts, particularly those affecting more vulnerable populations.[79]

Box 2.3

Rippling impacts of groundwater overexploitation in Jordan

In Jordan, 39 percent of irrigated agriculture is based on groundwater that is mostly mined, the abstraction rate being over 225 percent of the sustainable groundwater resource. The Country Climate and Development Report for Jordan,[1] published in January 2023, highlights the need for better groundwater governance. In the Azraq highlands, where the first wells were drilled in the 1930s, only in the 1960s did irrigated agriculture really started developing with diesel motor pumps. It boomed in the late 1970s and 1980s when modern irrigation and cropping techniques were introduced. Until the 1980s, tariffs and subsidized electricity and diesel, as well as subsidies for some field crops and stone fruits, contributed greatly to the growth of Jordan's agriculture. The absence of a policy to mitigate agricultural expansion and land exploitation dangerously spread agricultural investments in Azraq.

The expansion of agricultural land continued in the 1990s, dramatically increasing the water salinity and drying up the oases. To cope with such an impact of groundwater-based irrigation, the drilling of wells was frozen in 1992 when no licenses were given to new wells. In 1998, the Groundwater Management Policy was promulgated. In 2002, the Ministry of Water and Irrigation issued an Underground Water Control bylaw to control private agricultural abstraction, introducing quotas. Water meters were installed (on legal wells), and since 2004, farmers have been regularly receiving their water bills.

Groundwater over-abstraction was reduced only after 2004, thanks to the implementation of the institutional framework, combined with the steep decline in water tables, increasing groundwater salinity, and the rise of operational costs. While the groundwater table continued to fall, many farms were abandoned across the region, but no detailed survey was conducted. In 2010, the Ministry of Interior Affairs ordered the destruction of approximately 1,000 to 2,000 illegal farms younger than two years. The impact on poverty and agricultural production in the region was not measured. Solar pumping now emerges as a trump card, notably for illegal farms, which are challenged by recent tough water pricing regulations that make them unprofitable.

1. World Bank Group 2022.

Source: Demilecamps and Sartawi 2010.

Box 2.4

Sinking cities, surging costs: measuring groundwater-induced land subsidence in Jakarta

Measuring groundwater-induced land subsidence in cities is a challenging task, as many factors influence land subsidence, including natural tectonic subsidence. The nature of subsurface terrain determines whether a site is susceptible to land subsidence from groundwater extraction. This is the case if the terrain is unconsolidated. Where water is pumped from an aquifer that underlies a thick clay layer, the clay may compact as it is depressurized. Aquifer terrain itself can also compact when partly dewatered with the lowering of the water table, notably in areas prone to earthquakes that enhance such compaction. Locally, tall buildings, due to their higher mass, lead to higher subsidence. Urban subsidence can have irreversible impacts on critical infrastructure—failure, flooding, and the disruption of transportation and other services. Early action and regulation of pumping in areas prone to subsidence that leads to high impact are consequently critical. This requires coordinated efforts to assess and predict the physical and economic impacts.

Remote sensing tools that can provide information on emerging rates of subsidence at high spatial resolution are now being promoted. Interferometric Synthetic Aperture Radar (InSAR) has enabled the detection of changes in surface elevation at a resolution of several meters and is being promoted as a tool for mapping subsidence. However, their data require careful calibration with local GPS stations. Ideally, these would be used with information on the location and pumping rates of water wells and the subsurface soil maps, and evidence of subsidence from these tools could prioritize efforts to integrate local sources of information and project impacts.

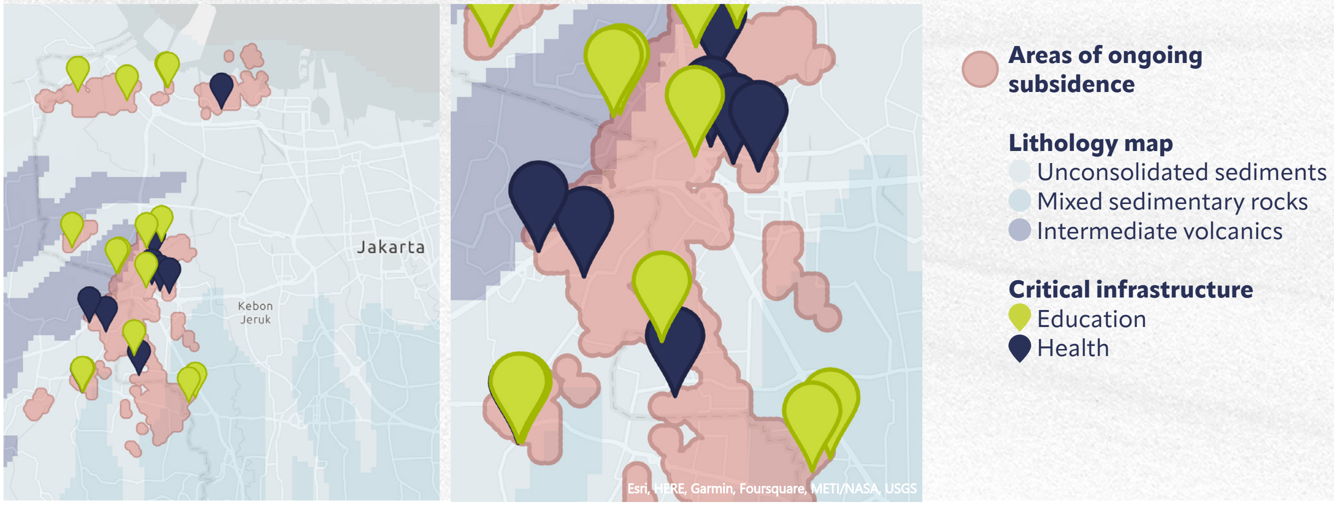
Such a granular, data-driven technique is employed for Jakarta. The map below shows a regional and close-up view of areas with ongoing land subsidence at rates that indicate a risk of infrastructural damage based on processed C-band Sentinel-1 A/B remote sensing data.[1] Most are built areas that include critical infrastructure, such as 12 health-related buildings and 15 schools. A structured approach to the problem would consider first the development of such maps to focus data collection and analysis on the possible pumping locations causing the most significant impact; a detailed physical and economic impact analysis; and policy formulation for regulating the pumping and the monitoring of future subsidence patterns. Such a global-local approach to data collection and analysis would provide for the documentation of uncertainties in each source of information and their valuation as part of an economics-driven strategy for urban resource management.

1. Wu et al. 2022.

Box figure 1

Regional and close-up view of land subsidence areas in Jakarta with symbols of critical infrastructure location

Source: Background paper for this report by Dinar, Lall, Prakash, and Josset (2023).



B

Degradation: Tainted water, compromised wealth

Complex hydrogeology with specific temporal and spatial scales makes the protection of groundwater quality a priority concern for its sustainable use. The quality of groundwater and its vulnerability to pollution is affected by many factors, including the natural rainfall regime and other natural recharge processes, hydrogeological settings, and anthropogenic activities. The thickness and hydraulic properties of the unsaturated zone and the presence of confining layers above the aquifer, and the hydraulic properties of the aquifer itself are the key factors determining groundwater vulnerability. However, the densification of economic activities increases the risks associated with groundwater contamination and the unknowns of how cocktails of different types of contamination interact.

Natural and human-induced groundwater contamination occurs at different scales, but the associated risks and costs demand attention before the impacts become irreversible. Groundwater quality is influenced by regional-scale climate factors and local-scale heterogeneous aquifer properties. One of the key challenges of groundwater quality management is to accommodate the multiple spatial scales of system processes and interests.[80] Unlike surface water processes, groundwater processes also occur at multiple temporal scales, with travel times ranging from days to millennia. The substantial time lags between cause, and effect makes it difficult to detect and understand groundwater contamination. And time lags between interventions and results also influence the remediation measures and management of groundwater quality. Remediation measures of deep groundwater contamination can be especially challenging with the long travel time, as deep groundwater may require millennia to flush. And by the time groundwater contamination is observed, remedial action is likely to be very expensive or technically impossible.

Groundwater is exposed to natural (geogenic) contamination. The natural chemistry of groundwater largely depends on the nature of the aquifer matrix. The major natural contaminants found in groundwater are arsenic, fluoride, and manganese[81] widely present, as well as radionuclides and heavy metals at numerous hot spots. Exposure to elevated concentrations can lead to cancer, heart and lung diseases, and dental and skeletal problems. Since the 1980s, natural contaminants have been recognized to be more extensive and substantial than previously thought.[82]

Nitrogen contamination is most concerning—for both its health threats and prohibitive costs of removal. Irrigation typically reduces groundwater quality through the percolation of fertilizer and pesticide and can also increase groundwater salinity (see Annex 5 on groundwater quality). Nitrogen pollution is the most influential global driver of human-made biodiversity decline after habitat destruction and the emission of greenhouse gases.[83] UNEP estimated that nitrogen costs the global economy between US$340 billion and US$3.4 trillion annually when considering its impact on human health and ecosystems.[84] Although it is known that oxidized nitrogen can be lethal to infants (commonly known as the blue baby syndrome), studies have also shown that those that survive endure longer-term damage throughout their lives due to stunted growth and impaired development in infancy, which could lead to poor productivity in later life.[85] According to the FAO, nitrates are the most common chemical contaminant found in groundwater aquifers worldwide, largely as a result of farming practices.[86] Furthermore, the presence of nitrates in groundwater is suspected to enhance the mobilization of other deadly pollutants, such as uranium, compounding the threat of groundwater pollution.[87]

Urban sludge is also an important source of contamination, particularly for local shallow aquifers—more so in the event of floods. It contains a wide range of contaminants, mixing into a toxic cocktail that can dangerously threaten aquifers. It is composed of phosphates, nitrates, and untreated sanitation (including bacteriological contaminants) of various byproducts from industrial and medical sites and of heavy metals, hydrocarbons, and other urban waste. Aquifers that are more easily accessible by individuals (local shallow and major alluvial) are particularly exposed. Private wells in urban settings risk becoming pathways of groundwater contamination, more so during floods. Beyond water-borne disease outbreaks, the direct threat to public health is largely unmonitored, pointing to a hidden crisis of considerable proportion and most affecting those in poverty and vulnerability without alternative water sources. In Indonesia, for example, groundwater quality is deteriorating rapidly, with 93 percent of groundwater samples exceeding national pollutant threshold levels, more than 70 percent of this contamination being attributed to leaking septic tanks and poor septage disposed of.[88]

Climate change increases existing salinity concerns, with coastal areas, where 40 percent of the world's population lives, most exposed. More than 600 million people (around 10 percent of the world's population) live in coastal areas that are less than 10 meters above sea level, while close to 2.5 billion people) live within 100 km.[89] Most of these people rely on groundwater extracted from coastal aquifers, exposed to the risk of saline intrusion from a combination of excessive pumping of fresh groundwater, sea-level rise, and other impacts of climate change such as increasing storm surge and natural or induced land subsidence. Seawater intrusion in coastal aquifers is now recorded in most coastal countries. The list of sites already impacted is long and growing, from Spain to Gaza Strip, from Senegal to Zanzibar, in Pakistan, Vietnam, or Indonesia, or on both the Atlantic and the Pacific coasts of the American continent. Given the costs associated with flushing out salt after contamination, such intrusion threatens the long-term quality and sustainability of those aquifers.[90]

Adding to the "toxic mix" of degradation threats, the rising demand for "climate action minerals" highlights the broader concerns that mining activity presents for groundwater quality. Mining is intensifying to meet the demand for electronics, batteries, and renewable energy needed for the green energy transition. Better monitoring and enforcement mechanisms are needed to prevent groundwater contamination. And a synthesis of the global groundwater impact of mining is urgently needed.[91]

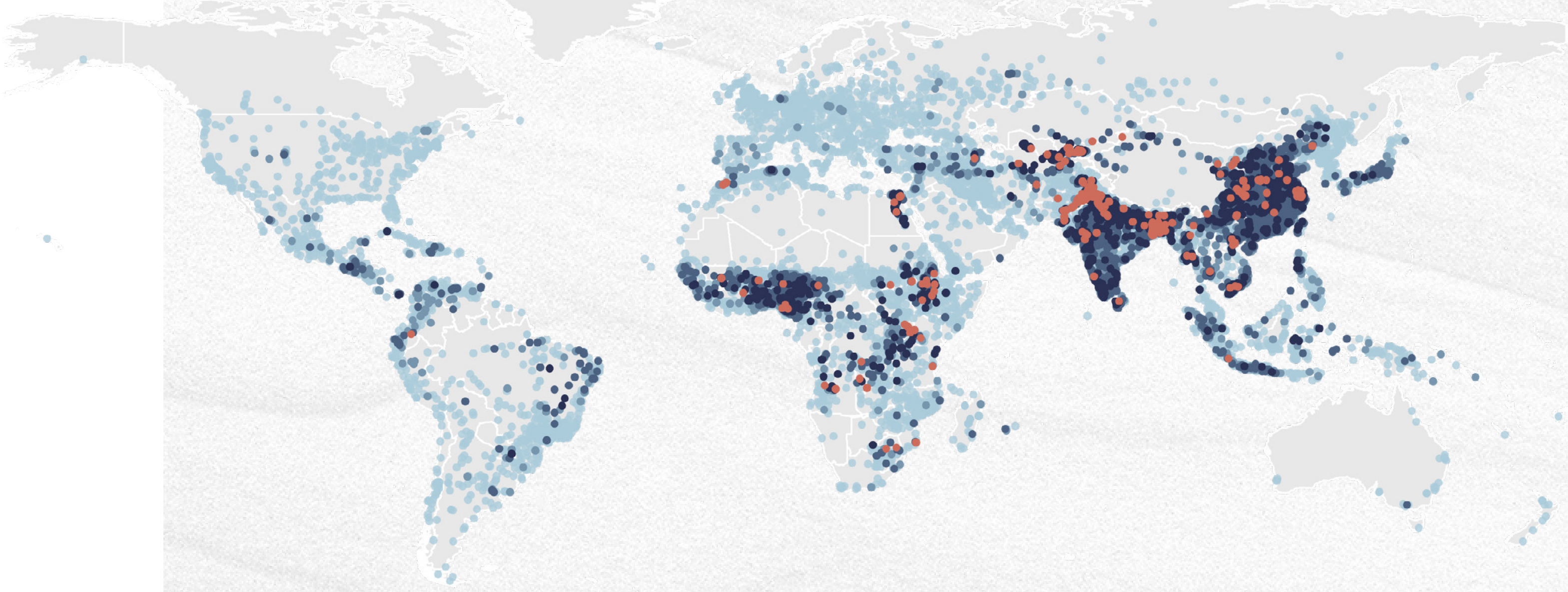
Competition: Precious wealth under pressure

Competition between urban and rural users for groundwater is heating up. By 2030, both Sub-Saharan Africa and South Asia will see most of their people reside in urban areas.[92] Cities have traditionally lifted people out of poverty, but there are concerns that frequent climate change-related shocks may slow down this effect.[93] And while denser types of urbanization can be economically and environmentally beneficial to cater to growing populations, they also involve well-known shifts in land use and less visible but equally critical changes in groundwater use and replenishment patterns. For instance, expanding urban footprints can reduce groundwater recharge through soil sealing. This trend is set to increase, with soil sealing expected to grow by 80 percent by 2050.[94] Increased urban demand and reduced groundwater recharge areas translate into growing urban groundwater stress—difficult to quantify due to the lack of complete global datasets of aquifer-specific changes. This can aggravate competition between groundwater uses across the urban-rural continuum (map 2.3).

More easily accessible groundwater from local shallow and major alluvial aquifers is most exposed to competition and degradation. Access to shallow groundwater allows urban migrants to gain access to water—directly or indirectly—where network access is unavailable. The largest urban sprawl is in Sub-Saharan Africa, where undeveloped land around cities over local shallow or major alluvial aquifers shrank by close to 21 percent over 2010–20. Such fast-paced low-density urbanization threatens the quality of those aquifers and their recharge process. It can also displace vulnerable populations from productive agricultural land and informal settlements where the lack of legal clarity in land tenure presents an additional obstacle to providing infrastructure and services.

Less visible competition for groundwater can have irreversible consequences for groundwater-dependent ecosystems (GDEs) and be a spark in the context of fragility. The Sahel is fragile, with high levels of poverty, exposure to weather shocks, and a recognized climate change hotspot.[95] Tensions over water between pastoralists and farmers are expected to be heightened by climate change.[96] Less well-known is the way GDEs are located on some of the key population routes and fragility hotspots. A machine learning–enhanced dataset of potential GDEs in dryland areas shows four well-known fragility and food insecurity hotspots (map 2.4).[97] Better understanding the interdependencies between GDEs, climate change, rural livelihoods, food security, and social stability as part of integrated policies and programmatic decisions is essential to reduce tradeoffs and inadvertent consequences.

Competition for groundwater may not always lead to conflict, but even the *status quo* can hasten its depletion. In Pakistan, groundwater in the Indus basin is most heavily used in Punjab and Sindh, where 88 percent of rural households lack piped water, and in parts of Khyber Pakhtunkhwa and Balochistan.[98] A substantial proportion of those households rely on springs, wells, boreholes, and other groundwater sources. While overexploitation of the major alluvial aquifer of the Indus Basin for irrigation is apparent in parts of Punjab, more extreme examples are in smaller alluvial aquifers that are part of complex systems, as in Kuchlagh in Balochistan, where overexploitation for agriculture has led to progressive depletion. Basic provisions governing access to groundwater and the restriction of groundwater use[99] were not implemented, and the aquifer gradually dried up. There was no conflict. Nor did the depletion trigger cooperation, the use of efficient irrigation methods, or the adaptation of local groundwater recharge measures—all because of a "socio-institutional void."[100]



Map 2.3

Groundwater availability is key to urbanization in developing countries but can compete with agricultural land

Source: World Bank elaboration using data on land cover classification from Copernicus Global Land Service and on land area equipped for irrigation classified by the Food and Agriculture Organization. The sample of cities is drawn from the European Commission's Global Human Settlement–Urban Centre Database R2019.

Annual average growth rate toward irrigated land 1992-2020

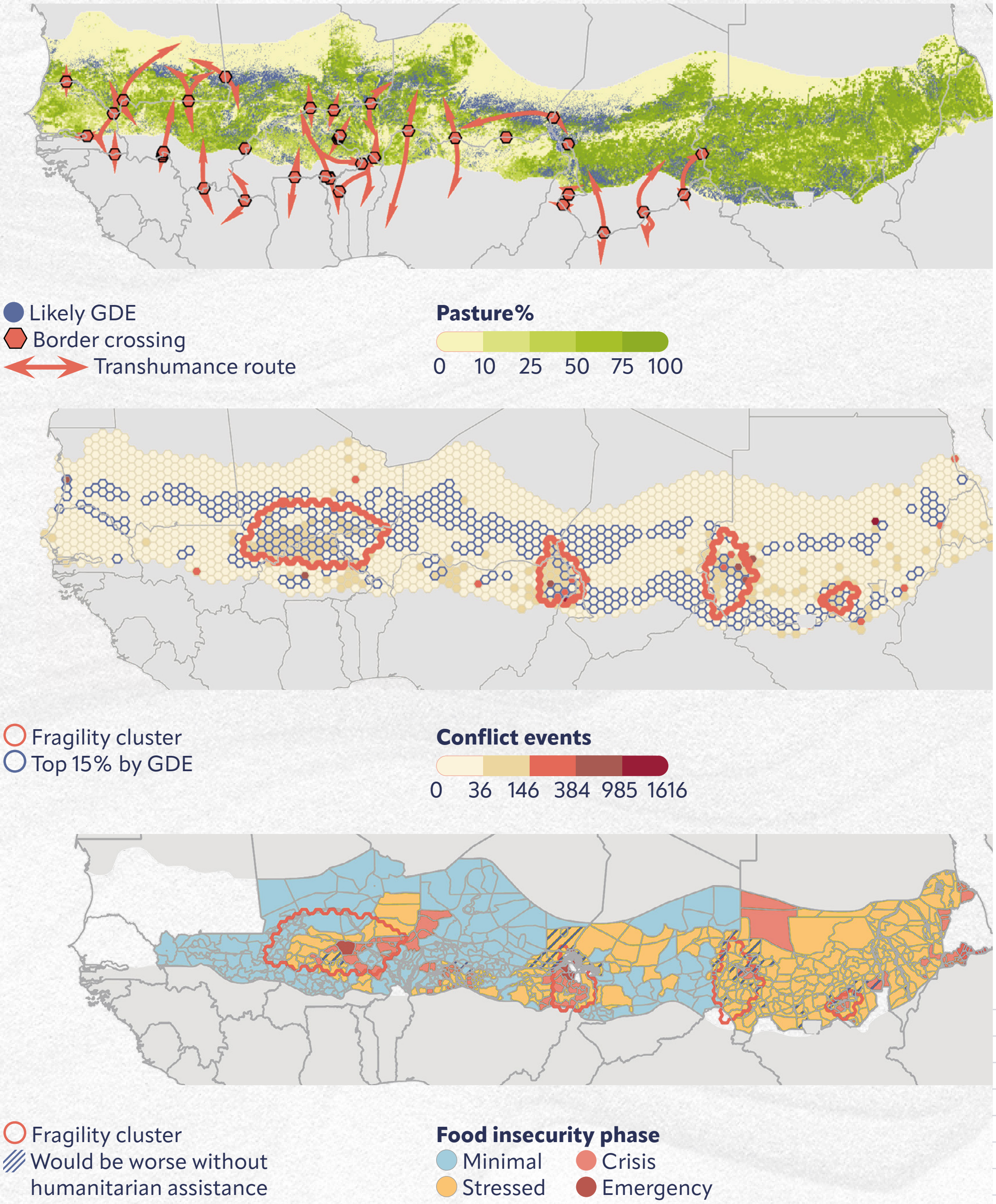
● 0-1%
● 1-2%
● 2-5%
● 5-10%
● +10%

Map 2.4

Groundwater-dependent ecosystems are at the crossroads of migration routes and fragility hotspots in the greater Sahel region

Source: World Bank using The Nature Conservancy GDEs data, (a) mapped GDEs and pastoral lands with transhumance pathways. (b) Transboundary fragility hotspot clusters based on grid-level cross between Armed Conflict Location & Event Data (all events between January 1, 1997, and February 2021, ACLED) and GDEs. (c) Food insecurity as of October 2021. Food security data is at the district level from the Famine Early Warning Systems Network (FEWS).

Note: The four hotspots are the Liptako-Gourma region at the borders of Mali, Burkina Faso, and Niger; the Lake Chad Basin at the borders of Chad, South Niger, Northern Nigeria, and Cameroon; the Darfur region at the borders of Sudan, South Sudan, Chad, and the Central African Republic; and the South Kordofan region between Sudan and South Sudan.



3

Getting the highest return

on a critical adaptation currency

Who owns groundwater? Growing intensity of use makes the question more pertinent. As a common-pool resource with open access, groundwater has no built-in ownership. Before the intensive use of the past half-century, ownership fell by default to landowners with a well on their land. Then in the 1960s and more in the 1990s, governments increasingly sought to vest ownership—or another legal status—in the state on behalf of the people and in the long-term public interests of equity and sustainability.[101] In these situations, customary private ownership has been replaced with rights that have been granted to users and regulated by the government (or stakeholders) through permits, licenses, concessions, and authorizations.

Beyond rights, asymmetric information shapes groundwater use: information gaps are a key challenge felt most acutely in developing countries, where institutional and enforcement capacities are weak. Asymmetric information constrains what policymakers can achieve in managing groundwater. Limited knowledge and monitoring of groundwater use and abstraction rates mean policymakers often operate with imperfect information about resource availability and quality. Water authorities might not even be aware of the location of boreholes and wells, especially when they are not registered. Some uncertainty can be reduced with better scientific knowledge. New technologies can contribute to reducing uncertainty. For instance, in East Asia, satellite imagery is used to measure evaporation, from which groundwater abstraction can be estimated, a method being considered in other parts of the world.[102] While such indirect methods cannot match the accuracy of *in situ* measurement, they can help in information triangulation to reduce uncertainty if transparently documented and peer-reviewed. Because eliminating uncertainty and asymmetric information is not a realistic short-term goal, policy reforms must find ways to factor in this uncertainty, moving toward integrated local and national water resource management.

Aligning private and social opportunity costs of groundwater use:

Three policy levers, four policy areas

Addressing the challenges and defining context-specific policies that account for multisectoral implications require activating three policy levers that form the core policy framework: information, incentives, and investment. The lack of adequate information about groundwater, including fundamental knowledge of the resource itself and how it responds to pressures, has resulted in both overexploitation and missed opportunities. When groundwater is taken for granted by users, it can lead to overexploitation and degradation. And when knowledge of groundwater's benefits is lacking, it can be underused, resulting in missed development opportunities. Inadequate information also means that policymakers are, by and large, operating blind when deciding on the equitable use of groundwater resources. Alignment of incentives, the second policy lever, is at the core of groundwater management, reflecting how the management of the resource transcends the mandate of the water institutions nominally charged with that task. Unless incentives at the user, institution, national, and transboundary levels are considered, policies to manage groundwater, however well-informed by scientific knowledge, will remain ineffective. Similarly, without the first two policy levers, the third lever, investment, will underperform at best or cause maladaptation at worst.

In aligning the private and social opportunity costs of groundwater use, policymakers can use these three policy levers in four main policy areas to determine which instruments to use and how to adapt them to the state of groundwater development:

1. *Policies that influence the marginal costs of abstraction* by increasing or lowering the costs of energy required to lift the resource from the ground. Energy subsidies and new technologies such as solar pumping or drip irrigation dominate this reform area.

2. *Policies affecting investments related to new drillings*, such as production or trade promotion subsidies that incentivize the expansion of groundwater-based irrigation.

3. *Policies relating to environmental externalities*, such as those affecting groundwater quality or downstream users, including groundwater-dependent ecosystems.

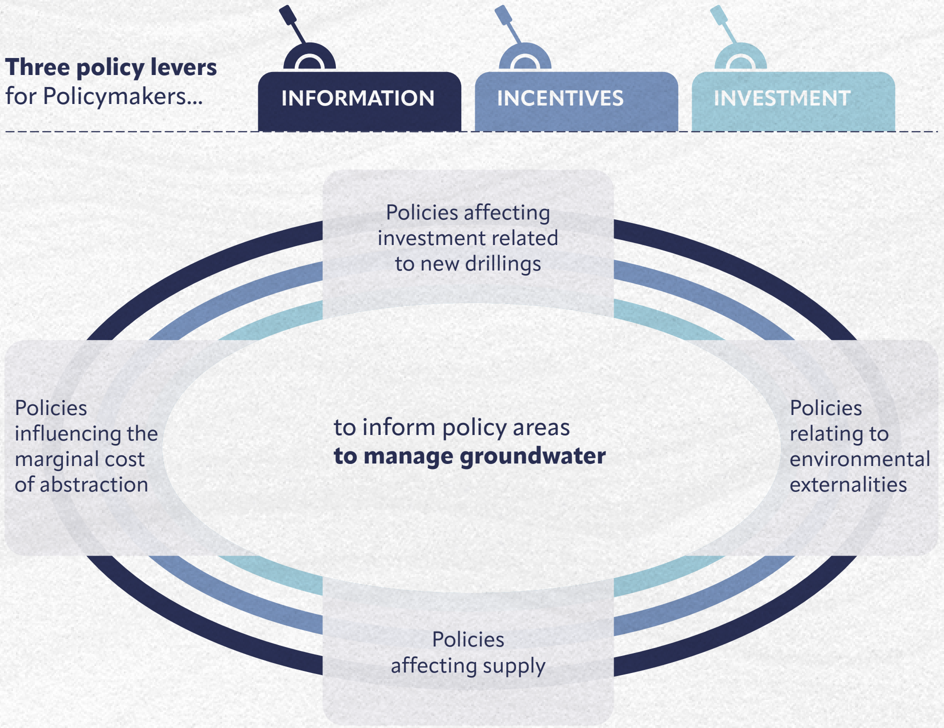
4. *Policies affecting supply*, for instance, by expanding enhanced nature-based recharge solutions or improving knowledge of the resource and the overall accounting and efficiency of investment related to groundwater to ensure that available supply is used efficiently and sustainably.

The Figure 3.1 below represents the policy levers and policy areas framing the choices and instruments that policymakers have at their disposal to mitigate the challenges of managing groundwater, given asymmetric information and groundwater's properties as a common-pool resource.

Where to start?

A systematically integrated approach combining cross-sectoral expertise and political leadership can deal with issues spanning from underuse to overexploitation of groundwater. Such an approach is urgently needed to leverage groundwater potential without risking negative externalities and, equally, to mitigate the consequences of overexploitation in other areas. The following sections discuss these policy areas and their links, reflecting on global examples that can inform the way forward (see Annex 6).

Figure 3.1
Policy levers and areas to mitigate the challenges of asymmetric information and common-pool resources



B

Not-so-marginal costs:

Revamping energy subsidies and using solar power

Adapting to climate change involves both energy and water dimensions. Groundwater is the most extracted raw resource globally, and its extraction has an important energy dimension. But without adequately considering groundwater, expanding access to greener energy—say, through solar pumping—could become a liability, with adaptation measures making people more, rather than less, vulnerable to climate change. Setting up maladaptation prevention policies, institutions, and investments ahead of a massive expansion of cheaper solar energy has to be a priority.

Investment returns from groundwater use are shaped by energy costs, and energy policies have so far incentivized groundwater overexploitation. Costs associated with groundwater are largely driven by fixed drilling costs for sinking wells and variable pumping costs related to pump maintenance and energy demand, which is affected by the overall depth of the water table, the extracted volume, and the unit cost of energy.[103]

Policies in the energy sector fuel groundwater consumption, particularly through subsidies. Previous work has shown the role of energy subsidies in increasing groundwater consumption in agriculture, especially when energy policies do not reflect the groundwater realities of the areas where they are implemented.[104] Despite dramatically different groundwater scenarios across India, energy policy is remarkably uniform with a federal system of government. Almost all Indian states subsidize power to agriculture by at least 50 percent of the average cost of providing it.[105] Awareness of this reality has grown and started to translate into pilot interventions to address the role of energy policies in groundwater overexploitation.[106]

Rapidly declining solar technology costs have made solar-powered pumps an appealing substitute for diesel and standard electric pumps. Solar technologies for groundwater-based irrigation are gaining attention as the price of solar pumps has fallen.[107] While diesel motor pumps remain overwhelmingly popular, solar pumps are an alternative with growing support. Solar pumps can be surface mounted or submersible and could thus provide an alternative to address the depth-cost relationship. Solar pumps remain more expensive than motor pumps in initial capital, but rapid technological advances can be expected to continue lowering the entry cost. Their low operation costs—solar pumps have virtually zero marginal costs to operate—make them a promising prospect.

Solar-powered pumping for irrigation can narrow access gaps in electricity, water supply, and irrigation. In Sub-Saharan Africa, access gaps in water and electricity tend to overlap, particularly in rural areas, and are leading drivers of multidimensional poverty. In addition, food security remains a concern for most African countries, with close to 25 percent of the population suffering from severe food insecurity.[108] The potential for solar energy is high in low-use settings, particularly for shallow groundwater abstraction. In high-use settings, the expansion of solar-powered irrigation/pumping has also been promoted by governments to reduce the cost of energy subsidies, fuel import bills, and carbon emissions.[109]

Easier access to solar technology enables expanding access to groundwater for irrigation and water supply, but with higher maladaptation risks, while the virtually zero marginal operating cost contributes to the greater complexity of policy responses in high-use settings. While low operating costs make solar pumping attractive, they also imply a higher complexity in regulating access to water use compared with electricity and fuel-based pumping. Once access has been achieved, users are incentivized to optimize their groundwater use to recuperate their pumping equipment investment and improve their agricultural income, but without considering wasteful water use. Subsidies for capital costs only scale up and speed this process. Preliminary evidence suggests that solar-powered irrigation may lead to more groundwater drawdown in both the short and longer terms.[110] For grid-connected pumps in Gujarat (India), the option of selling electricity back to the grid is not incentivizing a lowering of electricity consumption and thus has no impact on groundwater use.[111] For off-grid pumps, the increase in water use is even clearer. In Karnataka (India), an expansion of irrigated and cropped areas followed the conversion of a variable cost subsidy on electricity/diesel into a fixed cost subsidy on the capital cost of solar pumps.[112] And in Nepal, the subsidy and expansion of solar-powered irrigation led farmers to expand their agricultural livelihoods into aquaculture.[113] Wealthier farmers receiving solar pumping subsidies can also be expected to be a factor in increased and more inequitable groundwater use. Still, even in areas of high use in an adequate aquifer setting, the expansion of solar-powered irrigation can yield consolidated benefits.

In low-use settings, particularly in Sub-Saharan Africa, the lower cost of solar-powered pumping and the solar-irradiance potential make solar-powered irrigation a prime candidate for expanding irrigated agriculture and decentralized water supply in rural areas. Sub-Saharan Africa has undeniable potential to use groundwater to scale up irrigated agriculture. Based on solar irradiance and location suitability, it has among the highest levels of solar resources globally, especially in higher and lower latitude countries of West, Central, and Southern Africa and parts of East Africa.[114] So far, irrigated agriculture is still nascent there, with fewer than 4–7 percent of agricultural households irrigating. Solar water pumps have an estimated potential market of 5.2 million Sub-Saharan smallholder farmers. But affordability constraints place the addressable market potential at an estimated 0.64 million smallholder farmers.[115] And there are concerns about the design of policies and institutions capable of handling an equitable scaling up of solar-powered irrigation to capture the potential of the technology without threatening the sustainable use of groundwater or generating negative externalities.

Adapting to climate change depends on both energy and water dimensions, but without adequate consideration for groundwater, success in expanding access to greener energy—say, through solar pumping—could become a liability in the form of maladaptation. Unregulated expansion of solar pumping could lead to path-dependent maladaptation. Over 90 percent of Sub-Saharan Africa's groundwater-dependent ecosystems risk overexploitation if solar pumping is provided without adequate maladaptation safeguards. Setting up maladaptation prevention policies, institutions, and investments ahead of a massive expansion of cheaper access to energy is a priority.

Drilling incentives and behaviors:

Reforming producer subsidies

Governments across the globe support agriculture to the tune of $635 billion a year.[116] By influencing crop and irrigation choices, agricultural policies also affect groundwater abstraction and quality. And without reform of groundwater-sensitive agricultural subsidies, incentives to promote the sustainable management of groundwater will not be sufficient. To avoid undermining the returns to groundwater investment, action is needed at the highest political level to revamp agricultural policies and subsidies.

Producer support subsidies tied to production can lead to lower groundwater supplies. Cropped areas across the globe risk losing up to 13.2 cubic kilometers of water per year, which is roughly the total annual available groundwater resource in countries such as Chad, the Dominican Republic, or Guinea-Bissau.[117] Though broad and imprecise, this estimate suggests that coupled producer support subsidies have substantial implications for groundwater resources and can perceptibly deplete aquifers. In Haryana, India, the Mera Pani Meri Virasat Yojana project subsidizes rice producers to suspend growing this water-intensive crop in drought years when the aquifer recharge is reduced.

These aggregate impacts mirror patterns in country studies. Output subsidies—such as minimum support prices and government procurement contracts—directly affect agricultural markets and the price that farmers receive, skewing cropping decisions.[118] They have led to a 30 percent overproduction of water-intensive crops in India. In the northwestern state of Punjab, rice procurement accounted for 63 percent of the rise in groundwater depletion over two decades.[119] In the central state of Madhya Pradesh, wheat procurement beginning in 2007–08 has driven a 5.3 percentage point increase in dry wells and a 3.4 percentage point increase in borehole construction.[120]

Input subsidies also undermine groundwater quality. Fertilizer subsidies are some of the largest expenditure items in government budgets, with nitrogen more heavily subsidized than other fertilizers.[121] While beneficial to stimulate agricultural production, boost food security, and stabilize food prices, fertilizer subsidies may also encourage farmers to deviate from optimal practices, resulting in fertilizer use beyond recommended rates. That can diminish crop productivity and drive deterioration in groundwater quality.[122] Fertilizer and pesticide overuse is especially prevalent in South and East Asia and South American subregions. In areas where fertilizer input subsidies are above the country median, a 10 percent increase in fertilizer use causes 5.7 percent more nitrate to be stored in the vadose zone than in areas where the subsidies are lower.[123] As a result, subsidy-induced inefficiencies in fertilizer use can strongly affect groundwater pollution.

Of the groundwater depletion embedded in international agricultural trade, more than 60 percent comes from major alluvial aquifers. Most of the groundwater depletion embedded in the global food trade stems from water-intensive crops, starting with rice (close to one-third) and wheat (over 12 percent), but also including maize, cotton, soybeans, sugar, and citrus.[124] Two-thirds of groundwater depletion embedded in the global food trade comes from overuse areas in India, Pakistan, and the United States.[125] Trade promotion policies can also contribute to distorting incentives, compounding the effects of other policies.[126]

Some 30 percent of the world's food supply is lost or wasted, especially in developing countries, much of it due to policies that lower food prices or costs, such as production and consumption subsidies.[127] Governments also unwittingly incentivize food loss and waste by subsidizing inputs, including energy, water, and land conversion. Lower subsidies would have the same effect as higher food prices, resulting in less food loss and waste—outcomes needed even more in areas already experiencing groundwater overexploitation.

D

Replenishing the groundwater account:

Enhancing supply through groundwater recharge

Going back to the banking analogy, if groundwater withdrawals correspond to expenditure and are growing, policymakers need to ensure that balance is achieved by maintaining and enhancing the replenishment of the account through groundwater recharge. Indeed, if natural discharge and withdrawals exceed recharge, overextraction would compromise the long-term use of groundwater, and bankruptcy would occur if aquifer depletion jeopardized the "inheritance." To avoid this situation, policymakers can manage how much groundwater is extracted and ensure its quality is protected, echoing the first three policy levers previously discussed. However, they also have some margin in preserving and enhancing the natural aquifer recharge as part of integrated water management. Several approaches can be adapted to local contexts and integrated into cross-sectoral interventions like environmental or disaster risk management programs or as part of public work and labor market interventions (box 3.1).

Box 3.1

Increasing and protecting supply: Aquifer recharge and nature-based solutions

One of the main pillars of water management is to take advantage of the buffer capacity of the aquifers to store surface water or treated wastewater for further or downstream use. Infrastructures specifically dedicated to recharging water to aquifers are usually classified as managed aquifer recharge (MAR) infrastructures. Although popular, they suffer from strong limitations. First, they can be implemented only when the geological conditions are favorable (such as a shallow aquifer with thick unsaturated zone) and when raw water (such as river water, stormwater, treated wastewater, or any other raw surface water source) is available on a permanent basis. Second, proper implementation requires unique and specialized skills. Third, the implementation costs are substantial, with every additional cubic meter added to the aquifer costing between $0.4 to $1.4 per cubic meter, on average.[1] As a result, MAR is rarely implemented in developing countries and is particularly difficult in arid countries where surface water is not perennial.

An alternative to MAR is enhanced aquifer recharge that relies on landscape management and nature-based solutions (NBS). This technique refers to limiting rainwater runoff and increasing the soil retention capacity, enhancing the volume of aquifer recharge while preventing aquifer contamination. Enhanced aquifer recharge techniques are designed to assure adequate protection of human health and the environment and may also achieve other purposes, such as flood mitigation or reduced soil erosion.

Enhanced aquifer recharge is often associated with complementary techniques such as reforestation, agricultural terraces, and prevention of land clearing, which contributes to increased aquifer recharge. Stone bund building programs are locally implemented in many countries for soil and moisture conservation. Over generations, ethnic minorities of Nepal have used this technology to control soil erosion, promote water retention, and increase crop production.[2] It has a high probability of replication because it is simple to implement, low in cost, and makes maximum use of local resources.[3] In this way, enhanced aquifer recharge and NBS can ensure the protection of the quantity and quality of groundwater resources and enable the creation of *hydrogeological nature reserves*.[4] To date, such a concept has not been implemented at scale but has been adopted by private investors to protect bottled-water sources, especially in Europe.

Enhanced aquifer recharge activity also presents important labor-intensive job opportunities that could be part of public works undertaken as part of social protection and safety net programs. For example, reforestation is typically 100 days of work per hectare if done manually, each check dam is usually 5,000 to 10,000 working days in this configuration, manually constructed shallow wells are about 60 working days per well, and construction of trenches, canals, and terraces can all be done manually.

1. Vanderzalm et al. 2022.
2. Regmi et al. 2001.
3. van Zanten et al. 2023.
4. Marsily 1992.

Pulling all the policy levers:

Hard-learned groundwater management lessons

Regardless of the level of groundwater use, experience reveals that policymakers have three main policy levers at their disposal: information, incentives, and investment. Sustainably managing groundwater at scale is challenging, and few places have managed to do it beyond the local level. The main lessons that can guide policymakers' effective use of policy levers are fitting governance to the aquifer type and use, devising fit-for-purpose information systems that can close the gap between groundwater experts and decisionmakers, and nesting integrated and participatory management in target-based adaptive regulation frameworks.

First is fitting governance to the type of aquifer and its use. A review of the many experiences across the world in groundwater management reveals many trial-and-error approaches. Such a review also shows the importance of getting the right fit for a given local context by coordinating across sectors and borders.[128] Many failures in groundwater management—both in high governance capacity settings and in low capacity and difficult enforcement settings—reflect a failure to encompass aquifer specificities, as well as all the critical actors, issues, and incentives for success. Climate change raises the stakes and costs of not managing groundwater effectively. Many of the reforms needed to address groundwater overexploitation and degradation—and to prevent them where groundwater has been underused—are beyond the reach of groundwater management authorities, such as the influence of energy and producer subsidies on abstraction and drilling. But systematic changes are also needed in the water sector to empower the sustainable management of groundwater, starting with fitting governance to the type of aquifer and its uses.

Second is closing the knowledge gaps between groundwater experts and decisionmakers through fit-for-purpose information sharing and systems. While inadequate knowledge of groundwater is an impediment to managing this resource, global experience reveals a less recognized finding: the information about groundwater that is typically known by scientists and other experts is also available to decisionmakers—but the knowledge of how to use it best may be missing. Information is the lens through which the multidimensional implications of groundwater are refracted. Even in high-capacity settings like Canada, there is always more to learn about how to overcome the difficulties of integrating hydrogeological information into land-use planning activities.[129] And even when the needed hydrogeological information is available and validated, its pertinence still depends on its effective use and is conditioned by the quality of its adoption by non-specialists. This is more difficult when hydrogeological data are limited and uncertain, and groundwater specialists who can translate the information for decisionmakers are scarce. This lesson is critical to the design of groundwater management systems that enable informed decisionmaking and cross-sectoral collaboration.

Third is nesting integrated and participatory management in target-based adaptive regulation frameworks. Community participation has been widely recognized as an important component of sustainable governance of common-pool resources since the work of Nobel Prize winner Elinor Ostrom in southern California (United States) in the 1960s. The participation of local user groups in groundwater governance, especially through monitoring, is critical for raising awareness. Implementation of such an approach for selected aquifers in Morocco or India[22] demonstrates its interest. It is, however, insufficient to overcome the larger scale issues in groundwater management, particularly across both international and national borders, as shown by the groundwater stress in California, now one of the top 10 economies in the world. One example of integrated management is the European Union's Water Framework Directive (WFD). With close to 12,000 groundwater bodies in the European Union, it designed the WFD to provide a holistic water management approach for river basins requiring water quality, emission control, and groundwater protection, all of which must be understood within a given context. When implementing the directive, EU member states are free to organize their water administration as they see fit so long as they adhere to the leading principle of managing groundwater according to natural boundaries for river basins, most of the groundwater bodies fitting within these boundaries. The French basin directorate model is the most commonly adopted: in a basin committee setting, water stakeholders determine the management options to be implemented by the basin directorate. In many EU member states, implementation of the directive has shifted the main responsibility for groundwater issues from the municipal level to the basin level,[130] resulting in improved water quality and volume.

Making groundwater use a higher priority:

A call for urgent political action

This report reveals the urgency of a deep rethinking of groundwater management that extends beyond the sectors that rely directly on the resource. The three lessons just described should underpin this rethinking and inform the design of fit-for-context institutions, collaboration, and regulation systems affecting groundwater abstraction, drilling, and quality. But none of the lessons can be implemented without high political prioritizing of groundwater.

High-level political and cross-sectoral action is urgently required to align the private and social costs of groundwater use and to value and carefully manage this scarce resource properly. Managing groundwater requires integrated vertical and horizontal coordination. Vertical coordination entails the enhancement of regulatory frameworks for groundwater governance and the harmonization of policies from the local to the transboundary levels. In contrast, horizontal coordination requires sustained connections across sectors such as agriculture, energy, urban and rural development, and a central role for authorities charged with strategic development planning.

One impediment to this high-level prioritizing is the lack of capacity to account for all investments that rely on groundwater, which obscures the investment gaps in groundwater. This lack of capacity results from the absence of an identifying tag that adequately captures financial resources expended on groundwater. In addition, for groundwater abstraction assets such as wells and boreholes, financial investments too often focus on using the resource while underperforming in delivering water security, productivity, efficiency, and quality. Understanding specific geology and construction risks could significantly improve investment performance.

With groundwater no longer a hidden wealth, what should this high-level prioritizing entail?

Prioritizing the uses of groundwater should be informed not only by the type of aquifers but also by the level of use:

- **Underuse: improve knowledge of the resource and prioritize the development of local shallow aquifers, the ultimate "no-regret" value for farmer-led irrigation, improved food security, and climate shock buffering.** In low groundwater-use settings, what is most important is knowing how to derive the benefits of using the resource while avoiding the costs of overexploitation. Although groundwater literacy is vital at all levels of groundwater use, it is most critical in the earlier strategic planning stages when decisions can have long-term consequences for the sustainability of the resource, the benefits it will yield, and to whom. Interventions along the chain from policy to investments can have the most impact in low-use settings because they can determine the right balance of resource development and protection policies and establish the right institutions, enforcement mechanisms, and capacities.

- **Moderate use: protect groundwater quality and aquifer recharge for sustainability.** Two priorities take precedence in such settings: refining policy and institutions by learning from experience to adjust them to aquifer characteristics and socioeconomic context and prioritizing the protection of groundwater quality and quantity. Policies need to be clear about the pro-poor and welfare distribution effects of groundwater use, as well as being adapted to the type of aquifer. Based on such policies, management measures to reduce externalities should consider costs and benefits according to the type of water demand, aquifer properties, and social and institutional traditions. These measures should prioritize groundwater quality and quantity in the face of threats from salinity, nitrates, pesticides, and emergent pollutants, taking advantage of opportunities to course correct. Similarly, protecting and enhancing aquifer recharge has tremendous potential to increase groundwater availability, which is vital to respond to growing populations, urban development, and climate change.

- **Overexploited: diversify water sources and manage demand.** Where groundwater has been overexploited, needed reforms may come at a higher socioeconomic cost, and such costs are exacerbated by inaction. Deeper socioeconomic consequences may become tipping points even before the resource is exhausted. But exposure to the increasingly untenable costs of inaction in redressing overexploitation can spark a revaluation of the priority needs for groundwater and the urgency of reducing demand. Maximizing the value of groundwater requires valuing and accounting for its economic, social, and environmental costs and benefits; understanding local contexts and incentives; and considering unintended consequences and risks. In high-use settings, policymakers cannot be guided exclusively by a water-efficiency strategy. Equally important is reducing demand, including virtual groundwater trade, through more resource-friendly activities such as optimized crop selection, hydroponic crop farming, or feed production for fish and livestock. Diversifying sources through water transfer, reuse, desalination, and enhanced aquifer recharge can sustain groundwater as a strong asset in a water security portfolio.

Groundwater glossary

Aquifer is a geological formation, group of formations or part of formation that is saturated and sufficiently permeable to transmit economic quantities of water to wells and springs.

Aquifer productivity indicates the borehole yields that can reasonably be expected in different hydrogeological units. This parameter is used by some authors to describe the potential of an aquifer based on past borehole design and performance.

Aquifer recharge is the volume of water that enters an aquifer. Direct or diffuse recharge is the movement of snowmelt, rainfall water or floodwater into the soil, flowing downward through the unsaturated zone, until it arrives at the saturated zone of the aquifer. Indirect recharge occurs when the rainwater and snowmelt are concentrated on the ground surface through runoff, and infiltrates at discrete points. Recharge may also occur vertically or laterally from a river or a lake. Aquifers also receive underground recharge from adjacent, underlaying or overlaying aquifers. Recharge also refers to inputs of anthropic origin (irrigation returns, losses from drinking water from drinking water networks, artificial recharge, etc.).

Basement aquifer is a discontinuous aquifer developed within the weathered overburden and the fractures of basement formations, usually composed of hard, crystalline, or re-crystallized rocks of igneous or metamorphic origin with negligible primary porosity and permeability. It is characterized by its weak productivity, its local lateral extent, its limited depth (typically less than 100 m) and the strong influence of topography on the groundwater flow direction.

Complex porous aquifer and equivalent is used to describe aquifer system that is not a major alluvial aquifer nor a local shallow aquifer. The geologic reservoir may consist in one or more permeable formations such as large alluvial plain not included in the major alluvial category, or unconsolidated marine deposits, consolidated sedimentary deposits, layers or series of layers of old sedimentary tectonized terrain (typically sandstone and limestone, karstified or not), or volcanic terrain including basalt layers. The thickness of such aquifer system is often reported to be hundreds of meters.

Confined/Unconfined. A confined aquifer is an aquifer located below a formation of low-permeability materials (typically clay materials), causing it to be under pressure and fully saturated with water. When a confined aquifer is penetrated by a well, the water will rise above the top of the aquifer (and sometimes up to the ground surface). On the contrary, unconfined aquifer is an aquifer partly unsaturated, whose upper water surface (water table) is at atmospheric pressure. It usually corresponds to the first aquifer from the surface when there is no continuous low-permeability cover.

Externality. Externalities occur when decisions about production or consumption by one person affect someone else without this being considered by the decision maker. If one entity's action has a positive impact on another, the externality is defined as positive. A classic example of a positive externality is an agricultural example, where a beekeeper benefit neighboring farmers by supplying pollination services as an unintended effect of his/her production of honey, and from which the farmers' crops benefits. When the externality decreases the well-being or utility of the affected entity, it is defined as a negative externality. A typical example of a negative externality is pollution. The use of fertilizers in agriculture produces negative externalities such as surface and groundwater water pollution.

Groundwater Dependent Ecosystem (GDE) is an ecosystem that requires access to groundwater on a permanent or intermittent basis to meet all or some of its water requirements to maintain its communities of plants and animals, ecological processes, and ecosystem services.

Groundwater depletion is the inevitable and natural consequence of withdrawing water from an aquifer. The concept is usually limited to describing the substantial and continuous multi-year decline of the water table which represents the loss of aquifer storage resulting from withdrawals that exceed the average groundwater resource.

Groundwater flow. Groundwater moves underground through the pores of a geologic formation, or through open fractures or conduits respectively in fractured or karstic aquifers. The groundwater flow is the movement of water underground in response to the natural gradient of pressure. For all aquifers, and because of continuous (even though sometime very slow) recharge and discharge, the piezometric head (elevation of the water table) is not constant over an aquifer: spatial changes in piezometric heads and thus directions of groundwater flow are described by piezometric maps. The range of groundwater flow is from centimeters per day to many meters per day (and even more in some karstic aquifers). An aquifer reaches a hydrodynamic equilibrium when the piezometric map is stable, meaning when the groundwater flow is constant.

Groundwater mining describes withdrawals that exceed the average available groundwater resource and that cause a continuous multi-year decline of the water table. Some authors only talk of groundwater mining when the time to revert from an influenced situation of the groundwater flows (i.e., with abstraction) to the natural situation after ceasing abstraction is more than two human generations.

Groundwater resource, or sustainable groundwater resource, is the rate of groundwater flow that can be harvested indefinitely without causing unacceptable environmental or socioeconomic consequences, including severe lowering of the water table resulting in (often irreversible) changing flow pattern or adverse quality impacts. It does not correspond to a particular value that can be calculated according to a single rule but depends, within the limits of the average annual recharge, on the balance between benefits and impacts that each society decides to accept in an open and transparent process with the community.

Groundwater reserve is the stock of groundwater stored in the aquifer, mostly linked to the size of the geological reservoir and its porosity. In contrast to the groundwater resource, the reserve cannot be harvested sustainably.

Karstic aquifer is an aquifer hosted in a karst, usually defined as terrain with distinctive hydrology and landforms that arise from a combination of high rock solubility and well developed secondary (fracture) porosity. The karst is formed from the dissolution of soluble bedrock, mostly carbonate rock, such as limestone and dolomite. The list of karst features is long and includes variety of micro and macro surficial and underground objects (notably karrens or lapies, dolines or sinkholes, uvalas, poljes, blind and hanging valleys, sinking streams, caverns, ponors or swallow holes, potholes, and caves). The properties of karstic aquifers greatly vary in space and groundwater flow is more concentrated and more rapid than in the other aquifer types. There may be large quantities of water in a conduit, while borehole a few meters away may be dry if hitting only the matrix.

Local shallow aquifer is used to refer indistinctly to an aquifer classified either as basement aquifer or as shallow alluvial aquifer.

Major alluvial aquifer refers to an aquifer developed in large deep unconsolidated deposits often as thick as 200 to 300 m and composed of gravel, sand, silt or clay deposited in river channels or across floodplains. Irrigated agriculture is usually extensively developed in such plains and often results in an overexploitation of the groundwater resource (e.g. Mississippi Alluvial Plain in the USA, Mitidja plain in Algeria, Haouz plain in Morocco, Caplina-Concordia coastal aquifer system in the Atacama Desert shared with Peru and Chile, Indo-Gangetic Plain shared with India, Nepal and Pakistan).

Piezometer is a borehole, usually equipped with small diameter casing (typically 4″ or less) dedicated to the monitoring of the water level of the tapped aquifer. To prevent artefact measurements, no pumping is applied to this borehole.

Permeability coefficient, or hydraulic conductivity, is a hydraulic parameter of aquifers (L.T-1), measuring the resistance of a porous structure to the flow of water through it. The permeability coefficient is derived from the permeability of the geologic formation considering that the saturating fluid is water. Poorly permeable aquifers show permeability coefficient as low as 10-4 or 10-5 m/s, when it goes up to 10-1 or 10-2 m/s for permeable aquifers. The productivity of the wells is influenced by both the permeability coefficient and the thickness of saturated terrain.

Porosity is a measure of the void spaces in a geologic material as the ratio of pore volume to the total volume of material. Effective porosity is a measure of the volume in which fluid flow is effectively taking place and is recoverable, while the residual porosity is the porosity due to the pores not communicating between them or with the external environment. The porosity, also called total porosity, is then the sum of the effective porosity and the residual porosity. Even if linked, there is not a direct proportionality between porosity and hydraulic conductivity. For discontinuous aquifers, the porosity is described by the primary porosity, the intergranular porosity associated with the original texture of the geologic formation, and the secondary porosity, created through alteration of the rock, commonly by processes such as dissolution and fracturing.

Shallow alluvial aquifer is generally an unconfined aquifer, typically 5 to 50 m of saturated thickness, consisting of unconsolidated fluvial clay, sand, gravel, and pebbles within the valleys of present day or ancient stream and rivers. These low-lying areas are prone to flooding during the rainy season. The water table often fluctuates in response to discharge to the riverbed, to pumping, and to varying recharge by direct rainfall or from the river itself. Due to their shallow and unconfined nature, alluvial aquifers are susceptible to contamination, notably in urban settings.

Storativity, or storage coefficient, is a hydraulic parameter of aquifers (dimensionless), measuring the volume of water that will be discharged from an aquifer per unit area of the aquifer and per unit reduction in hydraulic head. For a confined aquifer, storativity results only from the rock and fluid compressibility while in an unconfined aquifer it relates to the effective porosity of the geologic formation. The storativity of the aquifer will impact how fast the impact of localized pumping or recharge will be reflected in the rest of the aquifer: the higher the storativity, the shorter the lag.

Water table, or groundwater table, describes, in unconfined aquifers, the upper limit of the portion of the ground fully saturated with water. The water table fluctuates both with the seasons and from year to year, as it is affected by climatic variations and by the amount of natural and anthropogenic groundwater withdrawals. By extension, it is sometime use to describe the hydraulic pressure in confined aquifers.

Ending notes

Chapter 1

1. De la Peña-Olivas 2010.
2. Aquastat n.d.; Margat and Van der Gun 2013.
3. Siebert et al. 2013.
4. United Nations 2022.
5. The Nature Conservancy and R. McDonald 2016.
6. "*For it is the rare, Euthydemus, that is precious, while water is cheapest, though best, as Pindar said*" in Plato in Twelve Volumes, Vol. 3 translated by W.R.M. Lamb. Cambridge, MA, Harvard University Press; London, William Heinemann Ltd. 1967.
7. World Bank 2023.
8. Beattie 1981; Fishman et al. 2011; Cuthbert et al. 2022.
9. Edwards 2016.
10. Beattie 1981.
11. Shah 2010.
12. Sekhri 2014.
13. Because groundwater is a common-pool resource, two externalities related to pumping can be identified: a "stock externality" relating to the lack of internalization of the value of the resource, extracting it too quickly, triggering unbridled competition threatening the sustainability; a "pumping cost externality" resulting from users not internalizing how their own extraction lowers groundwater levels, increasing extraction costs for other users, and particularly those located in the corresponding cone of depression (Burlig, Preonas, Woerman 2018; Pfeiffer and Lin 2012).
14. As Jacoby (2023) notes, policies that affect drilling do not necessarily affect pumping, but nearly all policies that affect pumping affect drilling. This means that given the costly investment needed for drilling, particularly for poorer farmers, the welfare implications of changing incentives on the drilling margin are potentially huge and underappreciated.
15. Because groundwater is a common-pool resource, two externalities related to pumping can be identified: a "stock externality" relating to the lack of internalization of the value of the resource, extracting it too quickly, triggering unbridled competition threatening the sustainability; a "pumping cost externality" resulting from users not internalizing how their own extraction lowers groundwater levels, increasing extraction costs for other users, and particularly those located in the corresponding cone of depression (Burlig, Preonas, Woerman 2018; Pfeiffer and Lin 2012).
16. Researchers such as Sekhri (2014) have used this water depth exploitation.
17. Deaton 2013; Damania et al. 2023.
18. Jain et al. 2021.
19. Shah 2010.
20. Jain et al. 2021.
21. Zaveri et al. 2016.
22. World Bank 2018.
23. Burney et al. 2010.
24. Pavelic et al. 2013. The study includes Burkina Faso, Ethiopia, Ghana, Kenya, Malawi, Mali, Mozambique, Niger, Nigeria, Rwanda, Tanzania, Uganda, and Zambia.
25. World Bank 2022.
26. Mendonça et al. (2017) estimate that perennial lakes, which are mainly GDEs, bury some 0.33 billion tons of CO_2 per year corresponding to about 1 percent of the present global CO_2 emissions.
27. Hydraulic lift is the process for some deep-rooted plants to take in water from lower, wetter soil layers and exude that water into upper, drier soil layers. This mechanism, beneficial to both the tree transporting water and the neighboring plant, is found in many natural tree-grass mixtures and ecosystems. It is particularly critical in dryland areas.
28. Adams 2013; Damania et al. 2017.
29. Zaveri 2022.
30. Jain et al. 2021; Taraz 2017.
31. BBC News 2022.
32. Damania et al. 2017.
33. Damania et al. 2017.
34. The sample average of the probability of stunting is 0.40 and experiencing dry rainfall shocks in infancy results in a 0.08 percentage point increase in the probability of stunting.
35. Mekonnen et al. 2022.
36. Zaveri et al. 2021.
37. World Bank 2023; Damania et al., 2020; Zaveri, Damania and Engle 2023 forthcoming.

Chapter 2

38. Noori et al. 2021.
39. Garduño and Foster 2010.
40. Fenichel et al. 2016.
41. Zaveri and Damania 2019.
42. Fishman 2018; Zaveri and Lobell 2019.
43. Jain et al. 2021.
44. Sekhri 2013.
45. Ryan and Sudarshan 2022.
46. Hornbeck and Keskin 2014; Fishman, Jain, and Kishore 2013.

47. Sekhri 2013, 2014.
48. As noted in Fishman and Zaveri (2023), quasi-experimental studies enabling causal inference of these impacts are almost entirely geographically concentrated in India or the United States. Evidence in the other parts of the world that experience severe depletion still needs to be improved.
49. Fishman and Zaveri 2023.
50. Noori et al. 2021.
51. Shah 2000; Sakthivadivel 2007.
52. Patel, Saha, and Shah 2020.
53. Liquidity constraints, access to finance, and risk-taking capacity are hypothesized to be the likely culprits (Fishman, Gine, and Jacoby 2023; Blakeslee, Fishman, and Srinivasan 2020; Sekhri 2022).
54. Sarkar 2011; Blakeslee, Fishman, and Srinivasan 2021; Sekhri 2022; Fishman, Gine, and Jacoby 2023.
55. Ameur et al. 2017; Faysse et al. 2011.
56. Kendy et al. 2003.
57. Wester 2008.
58. Blomquist 1992; Lopez-Gunn and Cortina 2006.
59. Sarkar 2012.
60. The paradox of 19th century English economist William Stanley Jevons is that increasing resource use efficiency increases consumption—in his case, coal; in ours, groundwater.
61. Postel et al. 2001; Tilman 1999; Foley et al. 2011; Fishman, Gine, and Jacoby 2023.
62. Blakeslee, Fishman, and Srinivasan 2020.
63. Solow 1974.
64. Hartwick 1978.
65. Allan 2007.
66. Fishman, Jain, and Kishore 2013 , Fishman and Zaveri 2023.
67. Boudot-Reddy and Butler 2022.
68. Srinivasan and Lele 2017; De Graaf et al. 2019.
69. Grogan, Prusevitch, and Lammers 2023.
70. Grogan, Prusevitch, and Lammers 2023.
71. Mexico City is suffering from one of the world's most remarkable land subsidence rates, up to 37 centimeters a year. Groundwater extraction–induced subsidence has been documented for over a century: surveys show that the total subsidence between 1891 and 1952 had reached 6.0 meters in the city center with the increasing groundwater abstraction and an additional 2.5 meters between 1952 and 1973. Subsidence continues even though abstraction has been greatly reduced. Indeed, the subsidence became so extreme in some locations (over 9 meters) that it threatened building foundations, sewer drainage, and transportation systems.
72. Negahdary 2022.
73. In response to the growing pressures, the Indonesian government, in a dramatic move in January 2022, passed a law to officially move the capital from Jakarta to an undeveloped jungle tract in East Kalimantan, Borneo. The new capital will be named Nusantara and will replace Jakarta as the capital in 2024.
74. World Bank 2021.
75. Woillez and Espagne 2022.
76. World Bank 2019.
77. World Bank 2021.
78. Herrera-Garcia et al. 2021; Lall et al. 2020.
79. See the background paper prepared by Dinar, Lall, Prakash, and Josset (2023) for this flagship on the Economic and Social Cost of Land Subsidence.
80. Jakeman et al. 2016.
81. The potential toxicity of manganese in certain groundwater was highlighted by WHO (2022).
82. Ravenscroft and Lytton 2022.
83. Landmark biodiversity agreement at COP15, December 2022.
84. UNEP 2019.
85. Zaveri et al. 2020; Damania et al. 2019; Jones 2019.
86. Mateo-Sagasta et al. 2017; Damania et al. 2019.
87. Nolan and Weber 2015.
88. World Bank 2021.
89. United Nations 2017.
90. Renard and Poller 2001.
91. Lall et al. 2020.
92. United Nations 2018.
93. Mukim and Mark 2022; Glaeser 2012.
94. Flörke, Schneider, and McDonald 2018.
95. Diffenbaugh and Giorgi 2012.
96. McGuirk and Nunn 2022; World Bank 2022.
97. This analysis was realized as part of a research collaboration with the The Nature Conservancy. The results are included in an upcoming paper (Rhode et al. 2023–under review)
98. Mansuri et al. 2018; Lytton et al. 2021.
99. For example, section 4 of the Balochistan Ground Water Rights Administration Ordinance 1978 provides for the designation of groundwater basins where permission is required before extracting groundwater. The government has the power to stop the extraction of groundwater by unauthorized persons.
100. Van Steenbergen et al. 2015.

Chapter 3

101. Burchi and Nanni 2003.
102. For instance, in China, as part of the Xinjiang Turpan Water Conservation Project.
103. Buisson et al. 2021.
104. In the case of India, see Badiani-Magnusson and Jessoe 2018.
105. Jacoby 2021.
106. One example is the *Paani Bachao, Paise Kamao* (PBPK) scheme in the Indian state of Punjab (Mitra et al. 2022). However, such programs can be difficult to reproduce even in the same country, for instance, in states with different experiences with respect to informal groundwater markets (IGM) and be challenged by other subsidies (output-based) since it incentivizes the production of water-intensive crops.
107. World Bank 2018.
108. FAO 2021.
109. In South Asia, solar-powered irrigation is expanding rapidly as a replacement for fossil fuel irrigation and for enabling irrigation access for those who may not have it. More than 80 percent of solar-powered irrigation pumps globally are in India, where federal and state

governments actively pursue solar-powered irrigation. They are keen to reduce energy subsidies for agricultural groundwater pumping, which are threatening the financial viability of state power utilities (Bassi 2018) and increasing fuel import bills (Shim 2017). For example, electricity subsidies in Punjab comprised 61 percent of the state's fiscal deficit in 2018–19 (Economic and Statistical Organization, Government of Punjab 2020).

110. Balasubramanya et al. 2023.
111. While low buyback prices may be a factor, it is not clear that this would happen with higher prices since pump owners often sell water to other farmers (Balasubramanya et al. 2023).
112. Balasubramanya et al. 2023.
113. Balasubramanya et al. 2023.
114. Efficiency for Access Coalition 2021.
115. ESMAP 2022.
116. Gautam et al. 2022.
117. Damania et al. 2023.
118. Chatterjee, Lamba, and Zaveri 2022.
119. Chatterjee, Lamba, and Zaveri 2022.
120. Chatterjee, Lamba, and Zaveri 2022.
121. Damania et al. 2023.
122. Damania et al. 2023.
123. Ebadi, Russ, and Zaveri 2023. Before pollution can be detected in groundwater, contaminants that accumulate in the subsurface spread vertically and laterally in the vadose zone, long before reaching the water table. As such, the amount of stored nitrate here provides a first glimpse into likely impacts on groundwater pollution over time.
124. Analysis done for this report based on Dalin et al. (2017) and using the new groundwater typology. See Wada (2023).
125. Dalin et al. 2017.
126. Sekhri (2022) shows that trade promotion through Agricultural Export Promotions Zones–AEZs in India led to increased extraction of groundwater and increased groundwater declines in areas officially considered overexploited with high social costs.
127. World Bank 2020.
128. Alvarado, Garrick, and Erfurth 2023.
129. Ruiz et al. 2016.
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Groundwater is our most important freshwater resource, but the lack of systematic analysis of its economic importance has evaded the attention of policymakers and the general public—threatening the resource. *The Hidden Wealth of Nations* offers new data and evidence to advance understanding of the value of groundwater, the costs of mismanagement, and the opportunities to leverage its potential.

At the global level, groundwater can buffer a third of the losses in economic growth caused by droughts and can protect cities against day-zero-type events. It is especially important for agriculture, where groundwater can reduce up to half of the losses in agricultural productivity caused by rainfall variability. By insulating farms and incomes from climate shocks, the insurance of groundwater translates into protection against malnutrition. In contrast, the lack of access to shallow groundwater increases the chances of stunting among children under five by up to 20 percent. In Sub-Saharan Africa, untapped groundwater irrigation potential could be key to improving food security and poverty reduction. Little land is irrigated there, but local shallow aquifers represent more than 60 percent of the groundwater resource, and 255 million people in poverty live above them. But depletion, degradation, and competition for groundwater threaten its sustainability and availability for future generations. Greater understanding of groundwater's benefits and costs informs the report's policy framework and recommendations. The findings also reflect on the issues policymakers confront when attempting to align the private and social costs of groundwater use. A central message of *The Hidden Wealth of Nations* is that action is needed: groundwater needs to be a political priority and should be carefully managed through integrated cross-sectoral action to benefit society, the economy, and the environment.

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