EXECUTIVE SUMMARY

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François Bertone
Editors

The economics of groundwater in times of climate change

The hidden wealth of nations

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This booklet contains the executive summary from The Hidden Wealth of Nations: The Economics of Groundwater in Times of Climate Change.

A PDF of the final book, once published, will be available at https://openknowledge.worldbank.org/ and http://documents.worldbank.org/. Please use the final version of the book for citation, reproduction, and adaptation purposes.

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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.

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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, Eileen Burke, Gaia Hatzfeldt, Sarah Keener, Amjad Khan, Talajeh Livani, Sanjay Pahuja, Gustavo Saltiel, Amal Talbi, Pieter Waalewijn, 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 - IGRAC). 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 (Center for Social and Environmental Innovation).

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 along with Joe Caponio edited the report. Francis Gagnon and the team at Voilà: 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.

Executive summary

1 Valuing hidden wealth

Understanding groundwater

Groundwater provides 49 percent of the water withdrawn for domestic use by the global population[1] and around 43 percent of all water used for irrigation, serving 38 percent of the world's irrigated land.[2] It also sustains ecosystems that depend on it almost everywhere, especially in climate frontier areas. Yet its importance has been underappreciated, undermining its potential for boosting growth, reducing poverty, and buffering against climate shocks. Hidden below the Earth's surface, this common-pool resource is subject to barely visible depletion, with impacts that can be difficult to reverse. Not valuing or undervaluing this natural capital undermines tapping its potential for development and threatens some hard-won gains in regions that have heavily relied on it.

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

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 — 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. Third, individual users tend to account for their own private costs and benefits and usually do not account for the value of groundwater to other users, future generations, or connected rivers, springs, and other surface water bodies. In this case, individuals' high pumping rates could be optimal for them - but detrimental to society. User perceptions of these costs and benefits also matter; information asymmetry can increase the likelihood of overexploitation. Faced with growing demand, those features prime groundwater for overexploitation in a classic "tragedy of the commons," on hypercharge because of climate change.

Accessing groundwater depends on how far it is below the surface and the cost of withdrawing 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 the 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 understanding of aquifer types and their potential risks.[3] Those characteristics also matter for the management approaches required to facilitate long-term sustainability,[4] reap the expected benefits,[5] manage the relationship between individuals accessing a common-pool resource,[6] and foster successful collaboration between local users for aquifer management.[7] Two aquifer types, local shallow and major alluvial, are priorities for development thanks to their potential for individuals to tap.

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.[8] Lowering the water table below this 8-meter threshold excludes users who can't afford additional drilling to outrun 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 over-extraction 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.[9]

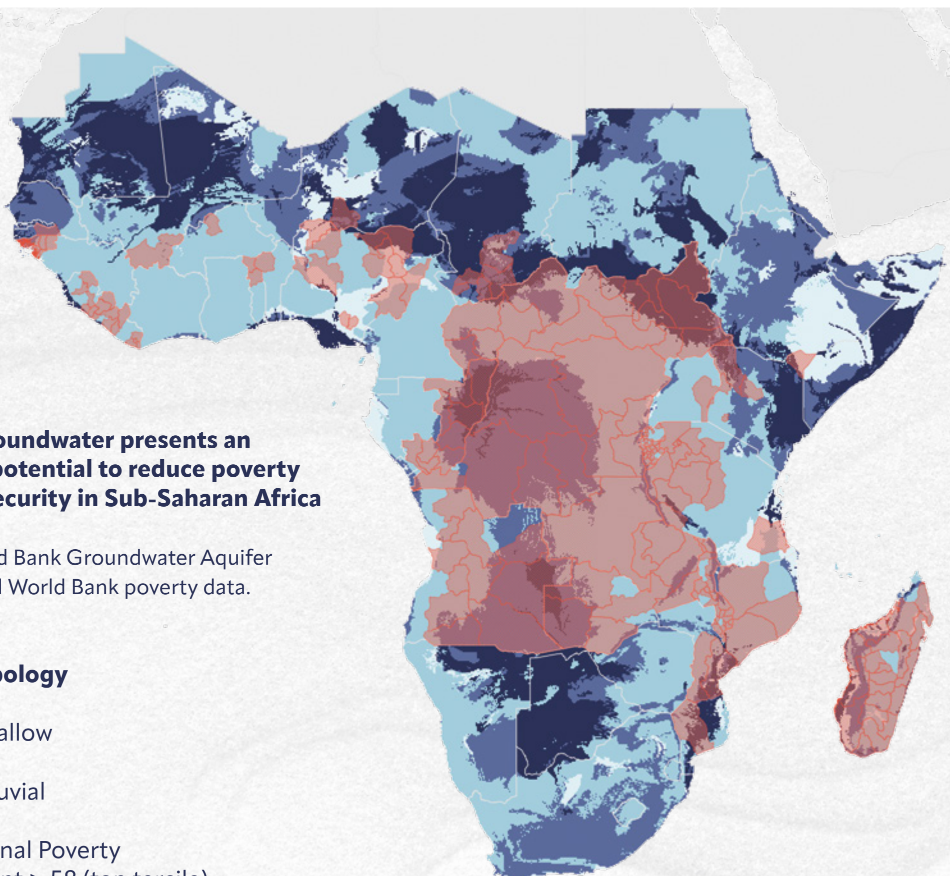
Certain types of aquifers are more exposed to the drawbacks of the common-pool characteristics of groundwater. In shallow aquifers (up to 8 meters below ground surface), pumps operated from the surface make groundwater economically accessible to individual farms and households. Local shallow aquifers offer the most potential from a development perspective, particularly in Sub-Saharan Africa, and have smaller overexploitation risks than other aquifers since they are fully replete seasonally. In contrast, the characteristics of major alluvial aquifers expose them to greater vulnerability to overexploitation. These aquifers are typically under large river flood plains and major valleys, and the amount of water drawn can be considerable. For them, drilling more than 20 meters down is typically required; boreholes can often reach 150 meters deep (e.g., Haouz in Morocco, Azraq in Jordan, or Sabarmati in India), and 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.

Environmental externalities affecting groundwater quality and dependent ecosystems also matter for poverty, intergenerational equity, and sustainable development. Externalities — the costs transferred to society that are 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, welfare costs may be the greatest for the drilling margins.[10] Environmental externalities are also shaped by policies not considering social costs, including groundwater quality.

Groundwater underpins the development of agriculture, cities, and critical ecosystems. Groundwater was one of the core ingredients of what the Nobel Prize-winning economist Angus Deaton calls the "great escape" from scarcity — and continues to sustain development.[11] Vast quantities of groundwater have sustained the intensification of agriculture brought on by the Green Revolution in various world regions. Millions of farmers depend on groundwater-based irrigation to help produce 40 percent of the world's crops, including a large proportion of staple crops like rice and wheat.[12] South Asia's 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.[13]

In India, groundwater-based irrigation directly sustains up to 20 percent of cropping intensity,14 28 percent of the total annual irrigated crop production, and more than half of dry season irrigated crop production.[15] And groundwater has been the backbone of water and food security in the arid and semiarid areas of North Africa and the Middle East. 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, groundwater 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. In Sub-Saharan Africa, groundwater is a key asset to increase irrigation, particularly at a small scale, with the growing affordability of technologies such as solar pumps.[16] In this region, more than 255 million people living in poverty ($1.90 line) reside in areas where expanding shallow groundwater is feasible and could reduce poverty by protecting people from climate shocks (Map 1).



Map 1.
Shallow groundwater presents an untapped potential to reduce poverty and food security in Sub-Saharan Africa

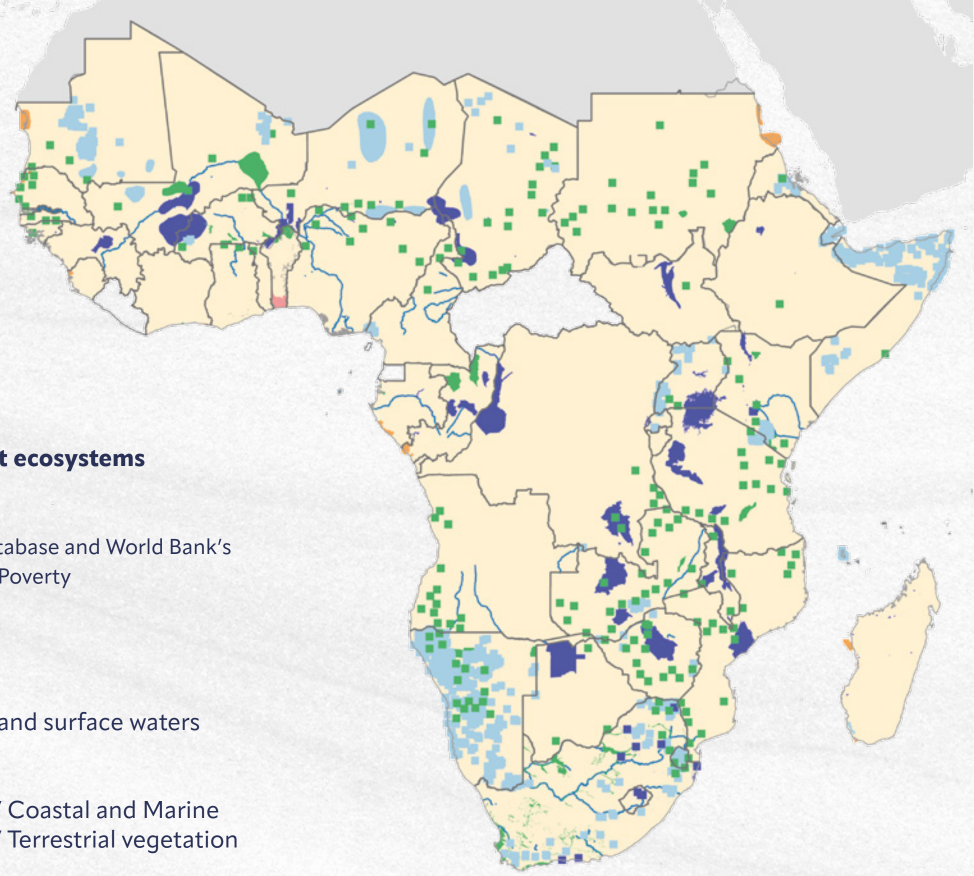
Source: World Bank Groundwater Aquifer Typology and World Bank poverty data.

Aquifer typology
- Karstic
- Local/Shallow
- Complex
- Major alluvial

- Subnational Poverty Headcount > 58 (top tercile)

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 water sources. In most developing countries, groundwater represents 60-90 percent of raw water intake points for domestic supply. In Sub-Saharan Africa, around 44 percent of the population relies on groundwater for drinking. On average, a quarter of the urban population in the region relies on groundwater. In Nigeria, this urban reliance rises to almost 60 percent. Groundwater has some key advantages in providing water for domestic purposes. First, decentralized groundwater sources can facilitate access in more recently developed areas of growing cities where network access is unavailable.[17] Second, its natural quality is typically high — if contamination is not a concern. Third, large aquifers have a large so-called capacity effect, helping to manage demand and buffering against dry shocks.

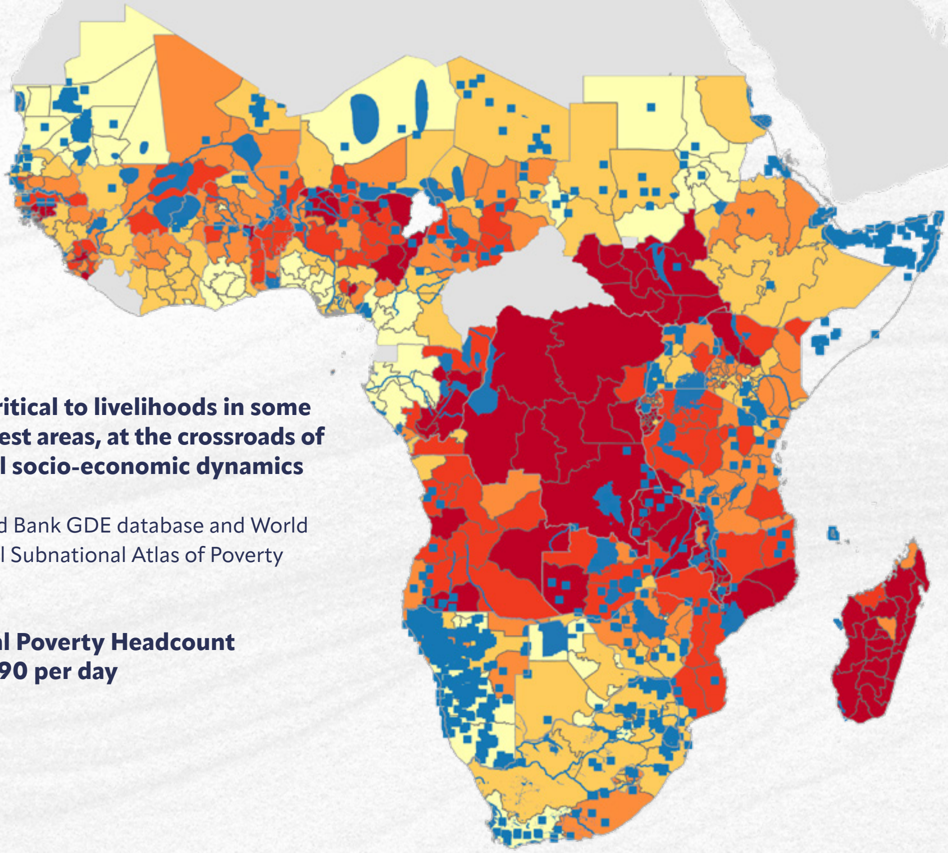
Less visible but equally critical, groundwater sustains a broad range of ecosystems critical to livelihoods. These groundwater-dependent ecosystems (GDEs) play roles that have been increasingly recognized over the past decade as part of the broader discussion around climate change and the recognition of their role as net carbon sinks.[18] 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 varieties of trees. New data on GDEs show that they exist in areas of high vulnerability to poverty, providing key socio-economic services in addition to their role in broader ecosystems (maps 2 and 3).[19]



Map 2.
Shedding a new light on groundwater-dependent ecosystems in Sub-Saharan Africa

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

GDE categories
- Inland surface waters
- Terrestrial springs / Inland surface waters
- Terrestrial vegetation
- Coastal and marine
- Inland surface waters / Coastal and Marine
- Inland surface waters / Terrestrial vegetation



Map 3.
GDEs are critical to livelihoods in some of the poorest areas, at the crossroads of crucial rural socio-economic dynamics

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

Subnational Poverty Headcount Ratio at $1.90 per day
≤ 14
≤ 33
≤ 52
≤ 69
≤ 98
GDE

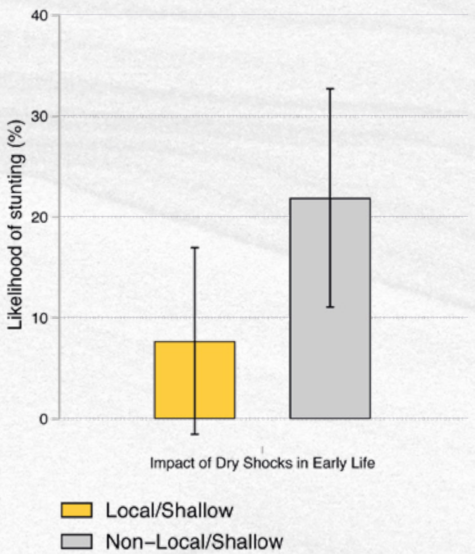
Groundwater's climate buffering is nature's multi-risk insurance

About 80 percent of the global population most at risk from crop failures and hunger from climate change are in Sub-Saharan Africa, South Asia, and Southeast Asia, where rural households are disproportionally poor and vulnerable. 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. Groundwater buffers against droughts because it can provide access to fresh water when surface water resources are scarce. In South Asia, climatic variability already leads to locally increased groundwater use.[20]

New analyses for this report show that by insulating farms and incomes from shocks, the insurance of local shallow aquifers translates into protection against malnutrition, particularly for children under age five. This is because individually accessible shallow groundwater has the potential to insulate agriculture from the adverse effects of rainfall variability — protecting food security and human capital. Without the natural buffer of 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. A new spatially disaggregated health database of 687,652 children across 32 countries in Africa spanning 15 years — shows that while rainfall shocks experienced in a child's earliest years can increase the likelihood of stunting, access to shallow groundwater has the potential to buffer against such harm. Indeed, not having such access raises the chances of stunting by up to 20 percent (Figure 1a).[21]

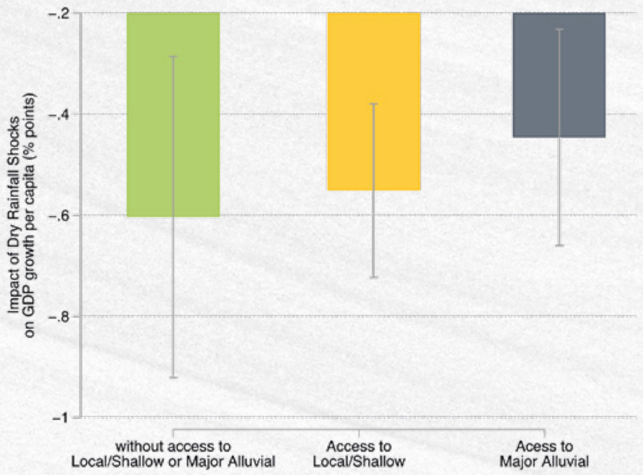
Figure 1.
Individually accessible groundwater prevents malnutrition in Sub-Saharan Africa (a) and protects global growth (b)

a. Stunting



Source: World Bank calculations using Aquifer Typology dataset (World Bank, 2023) and 32 Demographic and Health Surveys (DHS) in Africa

b. Economic growth



Source: World Bank calculations using Aquifer Typology dataset (World Bank, 2023) and Damania, R., Desbureaux, S. and Zaveri, E.(2020)

Together, groundwater's effects on farms, cities, and families cascade into overall effects on economic growth — with easily accessible aquifers shielding up to a third of the global losses in economic growth in the event of 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 1b).[22] This numerical result corroborates with known differences in aquifer systems. While major alluvial aquifers are vast, often regional, groundwater tanks with large buffer capacities that can overcome multiyear climatic shocks, local shallow aquifers have limited storage, so they benefit from seasonal recharge with full recovery and are more likely to be able to 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. Without action, vulnerability to climatic shocks will increase, leaving groundwater users and ecosystems high and dry.

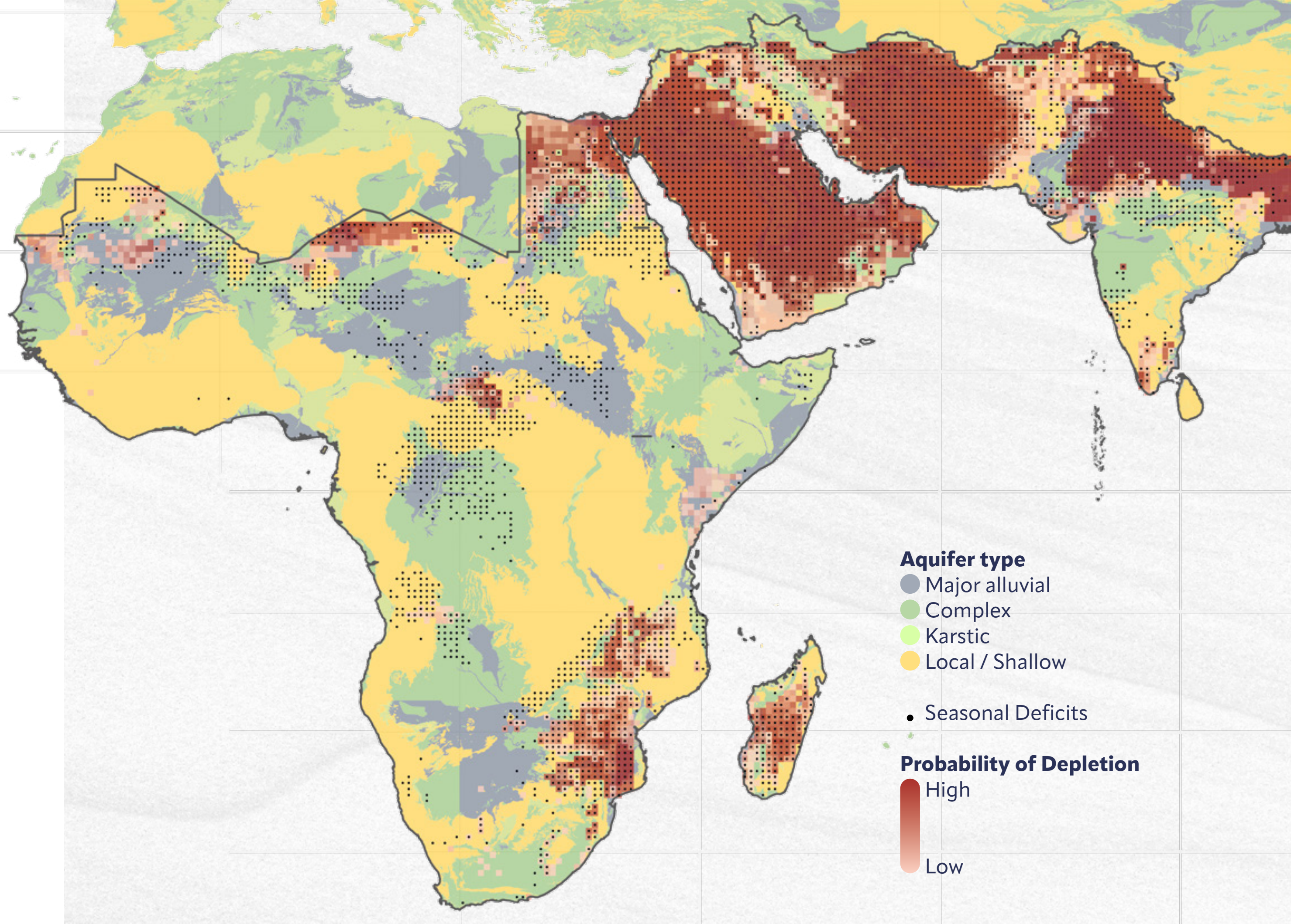
Depletion: Drawing Down Reserves, Draining Wealth

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.[23] As reliance on groundwater grows even as access to it dwindles, the impacts of drought and heat on water users could be greater in the future. Paradoxically, the groundwater resource that has cushioned climatic variability in the past may fail to continue attenuating its adverse impacts. Map 4 shows significant groundwater stress hotspots in the Indo-Gangetic basin, Iran, the Arabian Peninsula, and parts of Southern Africa. Moreover, up to 92 percent of trans-boundary aquifers in the study region show signs of dwindling groundwater levels.

Over time, the buffering benefits of groundwater are dissipating, with most of the impact driven by areas underlain by major alluvial aquifers that have experienced increasing declines in groundwater storage. These results corroborate country-specific analysis in India that shows groundwater played a buffer role against droughts and dry shocks up to the mid-1990s, providing a 10–20 percent agricultural revenue advantage, which disappears after 1995, possibly due to the lowering of groundwater tables.[24] In sum, the results suggest that depletion makes it harder to exploit the full potential of groundwater. Moreover, uncertainty induced by climate change will only add to this vulnerability as sustainable groundwater irrigation in the future becomes less feasible.[25]

The consequences of depletion are far-reaching — severely reducing farm output or, in a few cases, when embodied in land values. In India, cropping intensity can decline by up to 20 percent.[26] Food grain production can decrease by 8 percent in response to a 1-meter decline in the water table from its long-term mean.[27] 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.[28] More depleted areas can also face declines in land values or lease prices.[29] And groundwater depletion can increase poverty.[30] In areas with lower water tables, 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 mitigate the impacts of depletion fully.[31]

More importantly, groundwater's critical functions and services 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 would support groundwater-dependent ecosystems. Moreover, when water is used 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 impacts 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. Without groundwater, the surface water contributions to irrigation can decrease by up to 20%, impacting ~51,000 square kilometers of irrigated areas, some of which are across national borders from the depleted aquifers[32].



Map 4.
Declining trends and seasonal groundwater deficits

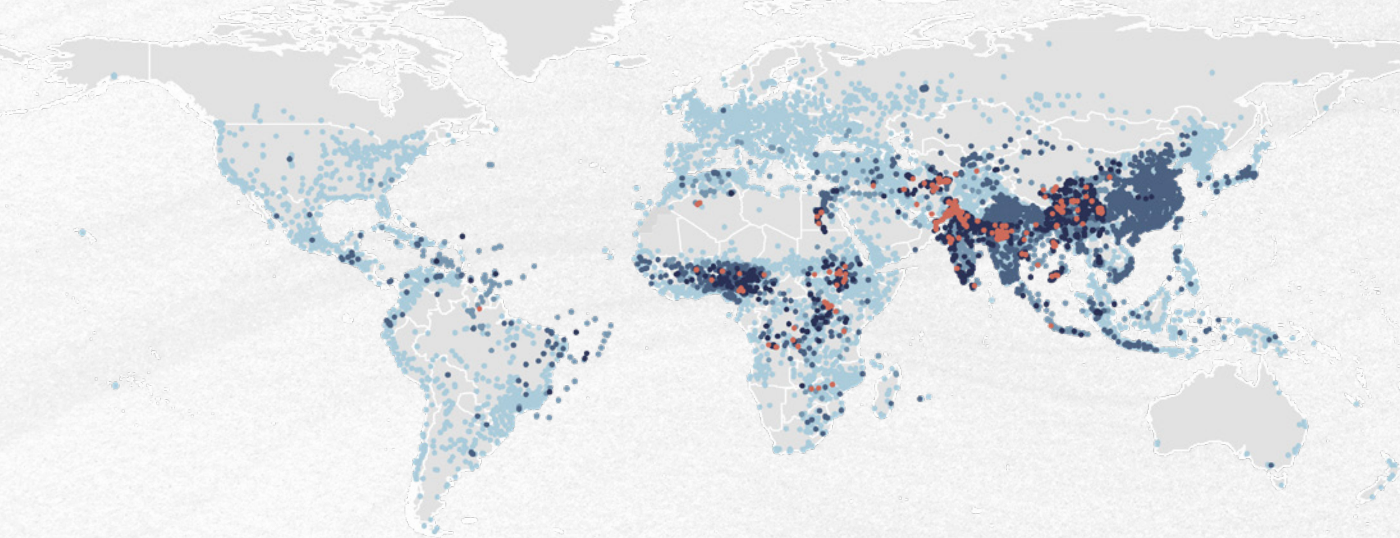
Source: Downscaled Gravity Recovery and Climate Experiment (GRACE) -observed groundwater storage (GWS) estimates prepared for the report (Chen et al., 2023).

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.

Staying solvent

Avoiding bankruptcy: managing competition and degradation

Competition between urban and rural users for groundwater is heating up. By 2030, Sub-Saharan Africa and South Asia will see most people residing in urban areas.[33] Cities have traditionally lifted people out of poverty, but there are concerns that frequent climate change–related shocks may slow down this effect.[34] 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.[35] 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 5).



Map 5.
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 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%

Box 1.

Groundwater at the frontline of climate change and fragility in the Sahel

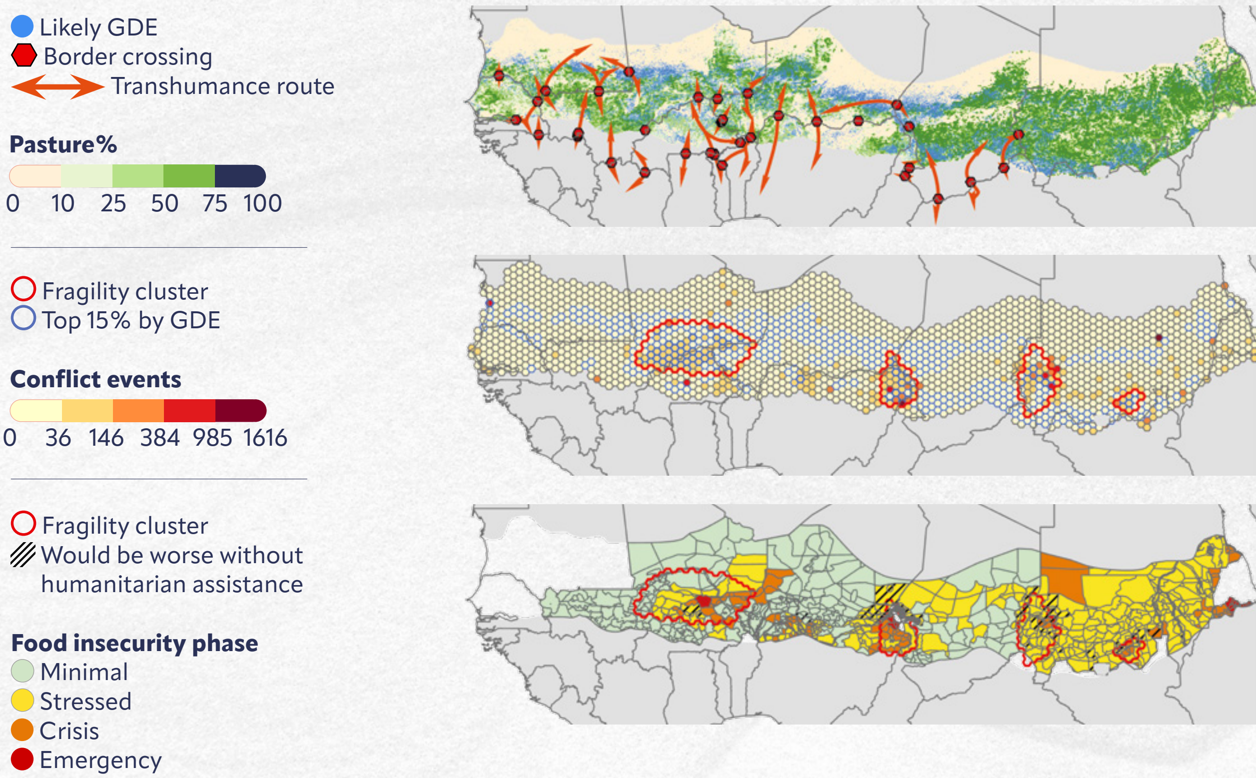
Less visible competition for groundwater can have irreversible consequences for groundwater-dependent ecosystems (GDEs) and be a spark in the context of fragility. The Sahel is fragile and a recognized climate change hotspot, with high poverty levels and exposure to weather shocks.[63] Climate change is expected to heighten tensions over water between pastoralists and farmers.[64] 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 in the Sahel (map 6).[65] 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 unintended consequences.

Map 6.

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.



More easily accessible groundwater from local shallow and major alluvial aquifers is also most exposed to competition and degradation. The complexity of the groundwater environment, with both temporal and spatial influences at multiple scales, makes protecting groundwater quality a challenge and a priority concern for sustainable use. The quality of groundwater and its vulnerability to pollution is affected by many factors, including natural rainfall regime and other natural recharge processes, hydrogeological settings, and anthropogenic activities. The thickness and hydraulic properties of the unsaturated zone, the presence of confining layers above the aquifer, and the hydraulic properties of the aquifer itself are the key factors determining groundwater vulnerability. Access to shallow groundwater allows urban migrants to access 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 nearly 21 percent over 2010–20. This could represent a challenge to peri-urban subsistence agriculture that needs better monitoring. 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.

Getting the highest return

from a precious climate adaptation currency

Who owns groundwater? With more intensive use, the question becomes 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 often fell by default to landowners with a well on their land. Then in the 1960s and more in the 1990s, many governments vested ownership in the state on behalf of the people and the long-term public interests of equity and sustainability, replacing customary private ownership.[36] The successful functioning of abstraction permit systems generally depends on proper knowledge of 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 government's weak capacity (and often political sensitivities) and the perception of the unfairness of the measures.[37]

Beyond rights, asymmetric information shapes groundwater use: it is a key challenge most acutely felt in developing countries where institutional and enforcement capacities are weaker. Asymmetric information constrains what policymakers can achieve in managing groundwater. They often operate with imperfect information about resource availability, and due to asymmetric information, monitoring groundwater use and abstraction rates is limited. Even identifying the location of boreholes and wells often eludes authorities – more so when unregistered. While some of this uncertainty can be reduced with better scientific knowledge of groundwater that can inform its potential uses, policy reforms must factor in this uncertainty, moving toward integrated local and national water resource management.

Policymakers confront four main policy issues when attempting to align private and social opportunity costs of groundwater use. These policies determine the potential instruments and how to adapt them to the state of groundwater development.

- First are **policies that influence the marginal costs of abstraction.** They include policies that affect groundwater pumping 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.
- Second are **policies affecting investments related to new drillings**, such as production subsidies that incentivize expansions of groundwater-based irrigation.
- Third are **policies to manage environmental externalities** such as those affecting groundwater quality or groundwater-dependent ecosystems.
- Fourth are **policies affecting supply**, for instance, through the expansion of enhanced nature-based recharge solutions. They also include 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.

Not so marginal costs: Revamping energy subsidies and using solar power

Adapting to climate change depends on energy and water, but 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.[38] To date, 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.[39] Awareness of this reality has grown and started to translate into pilot interventions to address the role of energy policies in groundwater overexploitation.[40] Yet subsidies are also being used to support the expansion of solar pumping, a technology with even less control over groundwater abstraction.

With virtually zero marginal operating costs, solar pumping could amplify existing over-abstraction and render policy responses all the harder in overexploited settings. Once access has been achieved, users are incentivized to optimize their groundwater abstraction to recuperate their pumping equipment investment and improve their agricultural income without considering wasteful water use. Subsidies for capital costs only scale up and speed up this process. Preliminary evidence suggests that solar irrigation may lead to more groundwater drawdown in the short and longer term.[41] For grid-connected pumps in Gujarat (India), the incentive of selling electricity back to the grid is not necessarily incentivizing a lowering of electricity consumption and thus has no impact on groundwater withdrawal.[42] For off-grid pumps, the increase in groundwater pumping 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.[43] And in Nepal, the subsidy and expansion of solar irrigation led solar farmers to expand their agricultural livelihoods into aquaculture.[44] Wealthier farmers receiving solar pumping subsidies can also be expected to factor in increased and more inequitable groundwater use. Still, even in areas of high use, in the adequate aquifer setting, the expansion of solar irrigation can yield consolidated benefits.

In low-use settings, particularly in Sub-Saharan Africa, the lower cost of solar pumping and the solar irradiance potential make solar 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 if targeting surface pumps. 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.[45] So far, irrigated agriculture is still nascent there, with less than 4–7 percent of agricultural households irrigating. Solar water pumps have an estimated potential market of 5.2 million Sub-Saharan smallholder farmers for tapping the local shallow aquifers. But affordability constraints place the addressable market potential at an estimated 0.64 million smallholder farmers.[46] Incidentally, there are concerns about the design of policies and institutions capable of handling an equitable scaling up of solar 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. However, 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.[47] Setting up maladaptation prevention policies, institutions, and investments ahead of a massive expansion of cheaper access to energy is a priority. Still, it will not be sufficient to prevent over-abstraction if not part of a wider multi-sectoral response reflecting the social costs of abstraction.

Drilling down on incentives and behaviors: reforming producer subsidies

Central to managing groundwater sustainably is how to reconcile the private costs of abstraction being different from the social cost of abstraction under asymmetric information. As previously seen, groundwater overexploitation is primed by its common property features in a classic "tragedy of the commons" scenario. Modern economics also suggests that an equally important attribute is asymmetric information. With asymmetric information, even without excludability issues, overexploitation would occur. With both excludability costs and asymmetric information, the problem is much worse since this narrows the feasible policy space. Agriculture subsidies further tip the equation towards private abstraction - rendering groundwater management more difficult, if not impossible.

Governments across the globe support agriculture to the tune of US$635 billion a year.[48] Since these policies influence crop and irrigation choices, they also affect groundwater supplies. And without groundwater-sensitive agricultural subsidy reform, innovative incentives that promote the sustainable management of groundwater alone 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 reduce groundwater supplies. Cropped areas across the globe risk losing up to 13.2 cubic kilometers of water per year, an amount that is enough to meet the drinking water needs of 500 million people.[49] Though broad and imprecise, this suggests that coupled producer support subsidies have substantial implications for groundwater resources and can lead to a perceptible depletion of aquifers.

These aggregate impacts mirror patterns in country studies. Output subsidies — such as minimum support prices and their procurement by government agencies — directly affect agricultural markets and the price that farmers receive and skew cropping decisions.[50] They have led to a 30 percent overproduction of water-intensive crops in India. In the northwestern state of Punjab (India), rice procurement accounts for 63 percent of the rise in groundwater depletion over two decades.[51] In the central state of Madhya Pradesh (India), wheat procurement adopted in the late 2000s has driven a 5.3 percentage point increase in dry wells and a 3.4 percentage point increase in borehole construction.[52]

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.[53] While beneficial to stimulate agricultural production, boost food security, and stabilize food prices, subsidies may also encourage farmers to deviate from optimal practices, resulting in the overuse of fertilizers beyond recommended rates. This is especially prevalent in South and East Asia and South American subregions. This can diminish crop productivity and drive deterioration in groundwater quality.[54] In regions with high fertilizer input subsidy levels where subsidy inputs are above the country's median, a 10 percent increase in fertilizer use causes a 5.7 percent greater quantity of nitrate stored in the vadose zone relative to areas where there are lower fertilizer input subsidies.[55] As a result, subsidy-induced inefficiencies in fertilizer use can strongly impact groundwater pollution.

Of the groundwater depletion embedded in international agricultural trade, more than 60 percent is 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%), but also including maize, cotton, soybeans, sugar crops, and citrus crops.[56] Two-thirds of all groundwater depletion embedded in the global food trade comes from over-depleted areas in India, Pakistan, and the United States.[57]

Making groundwater a higher priority: a call for urgent political action

Efficiency in production and consumption is possible. For instance, 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.[58] Governments also unwittingly incentivize food lost and wasted by subsidizing inputs, including energy, water, and land conversions. Lower subsidies would have the same effect as higher food prices, and food lost or wasted would decline — outcomes needed even more in areas already exposed to groundwater overexploitation.

But maximizing the value of groundwater requires valuing and accounting for all costs and benefits. It requires understanding local contexts and incentives and envisioning unintended consequences. It implies moving away from a water efficiency narrative prioritizing technological change over demand management. Local dynamics can challenge the external validity of a successful pilot or policy in one area, which is not reproducible in another.[59] Valuing and accounting exercises are even more needed in case of a technology change, as with drop nozzle irrigation in Kansas (United States), which lost about $110 million a year (2005 US dollars) of capital value because of groundwater drawdown.[60] This large loss resulted from a state-subsidized shift toward "highly efficient" irrigation nozzles, while return flows were not properly captured. Indeed, with standard irrigation techniques, return flows play an important role in groundwater recharge, as only a fraction of the total volume of water is lost to evapotranspiration. So, without reduced pumping, "water saving" technology such as drip irrigation can worsen groundwater depletion — a situation known as the Jevons paradox.[61] Similarly, growing the same crop in the same area but using less water to irrigate will not stop groundwater depletion.[62] Policymakers need to be aware that they can't rely exclusively on a water efficiency strategy: efficiency is needed but insufficient without reducing the demand.

The lack of capacity to account for all investments related to groundwater significantly reduces the visibility of investment gaps in groundwater and adds to the challenge of information asymmetry, thereby impeding the prioritization of essential investments for this common pool resource. This lack of capacity results from the absence of an identifying tag that adequately captures financial resources expended on groundwater, including for the preservation of its quality or enhanced recharge. Not only are existing financial resources largely invisible, but the efficiency of these investments is also a concern, as investments relying on groundwater availability would underperform or be compromised should the resource be threatened. Investments in groundwater abstraction assets, such as open wells and boreholes, too often fail to adequately capture geology and construction risks that could significantly impair their performance, including in some regions where they are most needed. A greater understanding of the benefits and costs associated with groundwater can help policymakers identify priorities and big-ticket items for their country. Priorities may vary depending on the level of abstraction and management of groundwater across countries: from those that have yet to fully harness the potential of the resource to those that have overexploited it and are suffering the damaging consequences.

- **Underuse: Start by improving knowledge of the resource and prioritizing the development of rapidly renewable local shallow aquifers, the ultimate "no-regret" value for farmer-led irrigation, improved food security, and buffering climate shocks.** Low groundwater-use settings need to prioritize knowledge about the resource to yield the benefits the resource can offer while preventing the costs associated with overexploitation. Groundwater literacy is key at all levels of groundwater use, especially in the earlier strategic planning stages when some decisions will have long-term consequences for the sustainability of the resource, the benefits it will yield, and to whom. Low-use settings are also where water-oriented interventions along the chain from policy to investments can have the most impact by setting the right balance of resource development and protection policies and the right institutions, enforcement mechanisms, and capacities.

- **Moderate use: Protect groundwater quality and aquifer recharge for sustainability.** Two priorities take precedence in such settings: first, refining policy and institutions by learning from experience to adjust them to aquifer characteristics and socio-economic context, and second prioritizing the protection of groundwater quality and quantity. Policies need to be clear to determine the pro-poor and welfare distribution effects of groundwater and need to be adapted based on the type of aquifers. Based on these policies, management measures to reduce externalities should consider costs and benefits depending on the type of water demand, aquifer properties, and social and institutional traditions. These measures should prioritize the protection of both groundwater quality and quantity: with salinity, nitrates, pesticides, and emergent pollutants condemning the use of the resource, opportunities to course-correct remain feasible; similarly, faced with increasing populations, urban development, and climate change groundwater availability can improve by protecting and enhancing aquifer recharge.

- **Overexploited: Diversify the portfolio of water sources and manage demand.** The longer they are delayed, the higher the probability for the needed reforms to come at a higher socioeconomic cost — exacerbated by inaction. Deeper consequences may become local or national socio-economic tipping points before the resource is even exhausted. But the exponential and increasingly untenable costs of inaction to redress overexploitation can also spark a re-valuation of groundwater through priority needs and reduced demand. By understanding the water balance and an ability to account for all its components, diversifying sources through water transfer, reuse, desalination, and enhanced aquifer recharge can sustain groundwater as a strong asset in a water security portfolio.

Ending notes

1. Aquastat n.d.; Margat and Van der Gun 2013.
2. Siebert et al. (2013).
3. World Bank (2023).
4. Beattie (1981); Fishman et al. (2011); Cuthbert et al. (2022).
5. Edwards (2016).
6. Beattie (1981).
7. Shah (2010).
8. Sekhri (2014).
9. 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).
10. As Jacoby (2023) noted, 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
11. Deaton (2013) ; Damania et al. (2023).
12. Jain et al. (2021).
13. Shah (2010).
14. Jain et al. (2021).
15. Zaveri et al. (2016).
16. World Bank (2018).
17. Nghiem et aL. (2023).
18. 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% of the present global CO_2 emissions.
19. 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.
20. Jain et al. (2021); Taraz (2017).
21. 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.
22. World Bank (2023); Damania et al., 2020; Zaveri, Damania, Engle (forthcoming).
23. Groundwater depletion refers to a sustained multi-year 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 (Fishman and Zaveri, 2023).
24. Zaveri and Damania (2019).
25. Fishman 2018; Zaveri and Lobell (2019).
26. Jain et al. (2021).
27. Sekhri (2013).
28. Ryan and Sudarshan (2022).
29. Hornbeck and Keskin (2014); Fishman, Jain, and Kishore (2013).
30. Sekhri (2013; 2014).
31. Note that 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 the world that experience severe depletion still needs to be improved (Fishman and Zaveri, 2023).
32. Grogan, Prusevitch, and Lammers (2023)
33. UN (2018).
34. Mukim and Mark (2022); Glaeser (2012).
35. Flörke, Schneider, and McDonald (2018).
36. However, not all governments followed this path, with Chile, India, Pakistan, and the state of Texas in the United States 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 (especially managed aquifer recharge) technologies. Finally, supporting and encouraging local-level self-management, which speaks to the solidarity of stakeholders and local action, is a common ground for possible avenues in these contexts.
37. Burchi and Nanni (2003).
38. Buisson et al. (2021).
39. In the case of India, see Badiani-Magnusson and Jessoe (2018).
40. Mitra et al. (2022).

41. Balasubramanya et al. (2023).
42. 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)
43. Balasubramanya et al. (2023).
44. Balasubramanya et al. (2023).
45. Efficiency for Access Coalition (2021).
46. ESMAP (2022).
47. Zuffinetti and Meunier (2023)
48. Gautam et al. (2022).
49. Damania et al. (2023).
50. Chatterjee, Lamba and Zaveri (2022).
51. Chatterjee, Lamba and Zaveri (2022).
52. Chatterjee, Lamba and Zaveri (2022).
53. Damania et al. (2023).
54. Damania et al. (2023).
55. Ebadi, Russ, and Zaveri (2022).
56. Analysis done for this report based on Dalin et al. (2017) and using the new groundwater typology. See. Wada (2023).
57. Dalin et al. (2017).
58. World Bank (2020).
59. Successful program like the Paani Bachao, Paise Kamao (PBPK) scheme in Punjab (Mitra et al. 2022) can be difficult to reproduce even in the same country. States with different experiences with respect to informal groundwater markets and presence of output based subsidies that incentivize the production of water intensive crops can impact the success of such programs.
60. Fenichel et al. (2016).
61. The paradox of 19th century English economist William Stanley Jevons is that increasing the efficiency of resource use increases consumption—in his case, coal; in ours, groundwater.
62. Jacoby (2017).
63. Diffenbaugh and Giorgi (2012).
64. McGuirk and Nunn (2022); World Bank (2022).
65. This analysis was realized as part of a research collaboration with The Nature Conservancy. The results are included in an upcoming paper (Rhode et al. 2023 – under review)

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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. The Hidden Wealth of Nations offers new data and evidence that advances 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 to 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. In contrast, 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. In this region, where little land is irrigated to date, local shallow aquifers represent over 60 percent of the groundwater resource: 255 million people in poverty live in those areas. But depletion, degradation, and competition for groundwater threaten its sustainability and availability for future generations. A greater understanding of groundwater's benefits and costs informs the report's policy framework and recommendations. The findings also reflect on the policy 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 politically prioritized and should be carefully managed through integrated cross-sectoral action to benefit society, the economy, and the environment.

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