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Annexes

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Esha Zaveri
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Editors

The economics of
groundwater in times
of climate change

The hidden wealth of nations

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ANNEXES

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Annex 1: Aquifer Typology: Four Aquifer Types and Their Key Characteristics

	TYPE OF AQUIFER	**EXAMPLES**	**ECONOMIC ACCESSIBILITY** in terms of fixed expenditure (CAPEX) and operational costs associated with accessing water	**RESOURCE AVAILABILITY** in terms of quantity endowment and possible uses	**BUFFERING CAPACITY** in terms of aquifer potential to protect from climate shocks
INDIVIDUAL ACCESS POSSIBLE	**Local shallow**	**West African basement outcrop** **Indian peninsula basement outcrop**	**Very high** Easy access by anyone (including individuals and very small users) High potential for farmer-led irrigation	**Dispersed** Low storage and high renewability Aquifer buffer recovers after seasonal rain events (no risk of long-term overexploitation) High potential for small-scale uses	**Low** Usually sufficient to overcome inter-annual but not multi-annual meteorological variability
	Major alluvial	**Indus River Plain aquifer in India and Pakistan** **Mitija plain in Algeria** **Caplina aquifer in Chile and Peru**	**High** River floods plains Typical aquifer system of irrigation plains Low CAPEX in middle-income countries is associated with the development of the local drilling market. Higher CAPEX in low-income countries Water level going down with overexploitation, resulting in increased OPEX (deeper drilling and deeper pumping)	**Continuously high** No limit on physical water availability, but high exploitation rates imply decreasing water-table levels	**High** Buffer capacity large enough to overcome decadal meteorological variation thanks to permeable and thick aquifers

INSTITUTIONAL INVOLVEMENT NECESSARY	**Complex**	**Nubian sandstone in Chad, Egypt, Libya, and Sudan;** **Senegal-Mauritanian aquifer basin in The Gambia, Guinea-Bissau, Mauritania, and Senegal** **Volcanic aquifers in the Horn of Africa**	**Medium** Accessibility very heterogeneous, with only limited areas where resource is accessible with limited exploration cost	**Spatially variable** Resource might be available at significant depth or in a specific structural context Complex aquifer systems often cover large areas and overall resource availability might be variable from one area to the other	**High** The buffer capacity varies in space, but complex aquifers are mostly thick and permeable enough to overcome multi-annual to decadal meteorological variability
	Karstic	**Dinaric karst aquifer system in Italy, Slovenia, Croatia, Bosnia, Montenegro, and Albania;** **Umm er Radhuma-Dammam aquifer system in Iraq, Kuwait, and Saudi Arabia**	**Very low** High exploration costs and high risk of dry boreholes (due to discontinuous aquifers) and mainly deep-water levels High entry costs due to required investments (exploration, deep drilling, and so on). Requires specialist knowledge	**Locally high** If risks are overcome, water may be available in large quantity Concentrated flow v. diffuse flow for most other aquifer types	**Medium** Due to the high permeability of conduits and hydraulic gradients, extra water can hardly stay in the aquifer. In addition, at aquifer scale, the storage volume of voids is limited

Source: World Bank. 2023. A global dataset of aquifer typologies and groundwater resources. Washington DC

Annex 2: What Economic Theory Tells us About Groundwater[1]

The purpose of this note is to lay out a consistent terminology, rooted in welfare economics, for discussing groundwater development. We shall focus on groundwater in agriculture, which, in most of the developing world, means smallholder farming. While the economic issues may be similar in the case of groundwater pumping for domestic purposes, especially in settings where extraction is highly decentralized, irrigation is the predominant use of groundwater worldwide.

Begin with a single groundwater user who maximizes the net value of **natural capital**, the discounted present value of the profit stream from resource exploitation. The assumption of a single user dispenses with **common-pool resource externalities**,[2] an issue taken up later. The assumption of wealth maximization abstracts from intergenerational consumption allocation, also addressed below. Finally, set aside environmental effects such as saline groundwater intrusion, land subsidence, and ecosystem degradation, with the caveat that such negative externalities could be of sufficient importance to alter the welfare considerations discussed in this note.

World Bank (2022) identifies a typology of aquifers that are readily accessible to individual smallholders: **major alluvial** and **shallow/local**. Alluvial aquifers are vast storage tanks for groundwater with replenishment through recharge from direct rainfall, surface flows, irrigation return flows, and lateral flow from connected aquifers. In the absence of recharge, groundwater from a major alluvial aquifer is a pure **exhaustible resource** like oil. In a shallow/local aquifer, by contrast, there are no water reserves available to mine. Pumping is limited by annual recharge and thus there is no question of long-run resource **depletion**, although (as we shall see below) **economic overexploitation**, the dissipation of resource rents through wasteful competition, remains salient.

A single user of a major alluvial aquifer maximizes the net present value of the natural capital subject to the law of motion for the water table. The change in water table depends on the rate of recharge and the rate of extraction, the latter which is driven by pumping costs. The marginal cost of pumping, principally the energy expenditure required for lift, is increasing in depth to water table. Starting from its natural state, the aquifer will be depleted at a rate determined by **Hotelling's rule** of intertemporal efficiency modified to account for the effect of the falling water table on future pumping costs.[3] Groundwater is an exhaustible resource during this phase, but eventually become a **renewable resource** as a steady state is reached in which the rate of extraction equals the rate of recharge; any further depletion of the groundwater reserve is constrained by the prohibitive marginal pumping cost.[4]

If we think of our single user as "society" and equate the capitalized value of groundwater resources to social welfare, then what has just been described is the socially optimal depletion path. In other words, in terms of social welfare, some long-run depletion of major alluvial aquifers is preferred to no depletion whatsoever. **Sustainability** in its strongest sense of a constant natural resource across generations is inconsistent with optimal groundwater exploitation. The resource economics literature, however, considers **weak sustainability**, efficient extraction coupled with weakly rising consumption (or, equivalently, utility) across generations. **Hartwick's** (1977) **rule** describes how **intergenerational equity** can be attained in a closed economy by investing all rents from natural resource exploitation into productive capital, somewhat as Norway does with its sovereign wealth (oil) fund.[5]

While groundwater depletion can thus be weakly sustainable in principle, is it so in practice? Imagine decentralized exploitation with thousands of smallholders independently optimizing their extraction/consumption intertemporal profiles. The issue of weak sustainability then boils down to how the subjective discount rate of the typical groundwater user compares to the market rate of return. If groundwater users are relatively patient, then each one of them (like Norway) would save during the early extraction phase to provide their children an equal or higher living standard than they currently enjoy. With relative impatience, however, weak sustainability can fail on two fronts: First, parents want higher consumption than their children thus violating intergeneration equity. Second, if borrowing against future groundwater proceeds is constrained, then extraction is faster than under Hotelling's rule. So, decentralized groundwater extraction need not meet either the ethical or efficiency criteria of weak sustainability.

The case of many well-owners pumping from the same major alluvial aquifer under the rule of capture also introduces **competition** into the common-pool resource, leading to a **pumping-cost** and a **strategic externality**. The first externality arises because each farmer's pumping lowers the water table and thereby increases every farmer's pumping costs; the second externality arises as each farmer attempts to appropriate the contents of the aquifer, over which property rights are ill-defined. While these distortions lead to faster groundwater depletion than under single-user management, empirical calibration studies persistently find extremely low social costs associated with competition, a result known as the **Gisser-Sanchez Effect (GSE)**.[6]

Although suggesting minimal harm from competition, GSE studies implicitly treat investment in extractive capital (water wells and pumping equipment) as a sunk cost, thus ignoring the decision to *enter* the aquifer in the first place. Once entry is allowed, resource rents are prone to **dissipation**. In the case of a major alluvial aquifer with high transmissivity (a "bathtub"), the Nth water well sunk can, essentially, extract 1/Nth of the groundwater. Farmers will install wells until the expected return from doing so just equals investment cost, the standard (ex-ante) zero-profit condition. Notwithstanding the trivial social welfare gains from restricting pumping (i.e., the GSE), entry drives social welfare *net of capital investment* to zero![7] Economic, if not resource, overexploitation can happen on shallow/local aquifers as well, albeit to a lesser degree. Given the low transmissivity, along with localized and disconnected groundwater sources, drilling the marginal well in a shallow/local aquifer may add net social value by recovering groundwater that would not otherwise have been exploited. Nevertheless, if there is **well interference**, so that the pumping capacity of wells located next to each other are mutually attenuated, then some rent dissipation still occurs as more wells are sunk. Government subsidies to crop and (especially) to electricity prices, prevalent in many low-income settings, only exacerbate over-drilling. In short, competitive pressure on a common-pool groundwater resource may be far from benign.

To summarize, we cannot presume that groundwater extraction, decentralized across millions of smallholders, is economically efficient, let alone (weakly) sustainable. Policy reform -- be it some form of taxation of new wells or simply the removal of distortionary subsidies – can thus improve matters. That said, it is important to consider the state of groundwater development in formulating government interventions and to move cautiously on the regulatory front. Regions where farmers have heavily exploited groundwater resources over past decades (e.g., northwest India) have seen impressive economic growth and poverty reduction. Even if these aquifers eventually dry up, many of the (now well-educated) children of these farmers will have long moved on to relatively high-paying employment in the non-agricultural economy. Again, putting local environmental considerations aside, it is not obvious that these children (and their eventual children) would have been better off in a counterfactual world in which groundwater exploitation was so restricted from the outset that these aquifers never dried up.

Notes

1. This note was prepared by Hanan Jacoby (Lead Economist, DEC).
2. Common-pool resources are rivalrous in consumption and non-excludable to some extent, with an open-access regime representing the limiting case of perfect non-excludability.
3. Hotelling's (1931) rule states that marginal profit (resource revenue minus extraction cost) should increase at the rate of interest, or more slowly than the rate of interest once the future pumping cost effect is accounted for.
4. A corollary is that advances in technology that lower pumping costs may lead steady state water levels to drop. Note that, aside from nonzero replenishment, the existence of a steady state requires that the marginal extraction cost exceeds the marginal valuation of water. Otherwise, optimality dictates draining the aquifer entirely.
5. Groundwater from a particular aquifer may differ from oil and other extractives insofar as it directly enters household utility by providing, say, drinking water (and there are no close substitutes available, such as groundwater from another nearby aquifer or from a surface source). In such cases, intergenerational equity in utility may be inconsistent with efficient extraction and thus weak sustainability may be unattainable.
6. Gisser and Sanchez (1980) is the seminal article; see Koundouri (2004) for a later survey and Rubio and Casino (2001) for a game-theoretical treatment that accounts for both types of externalities.
7. Note that not merely the marginal well sunk has zero social return, but all wells in the aquifer, since each entails the same investment cost and yields the same amount of groundwater.

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Annex 3: Groundwater Dependent Ecosystems (GDEs)

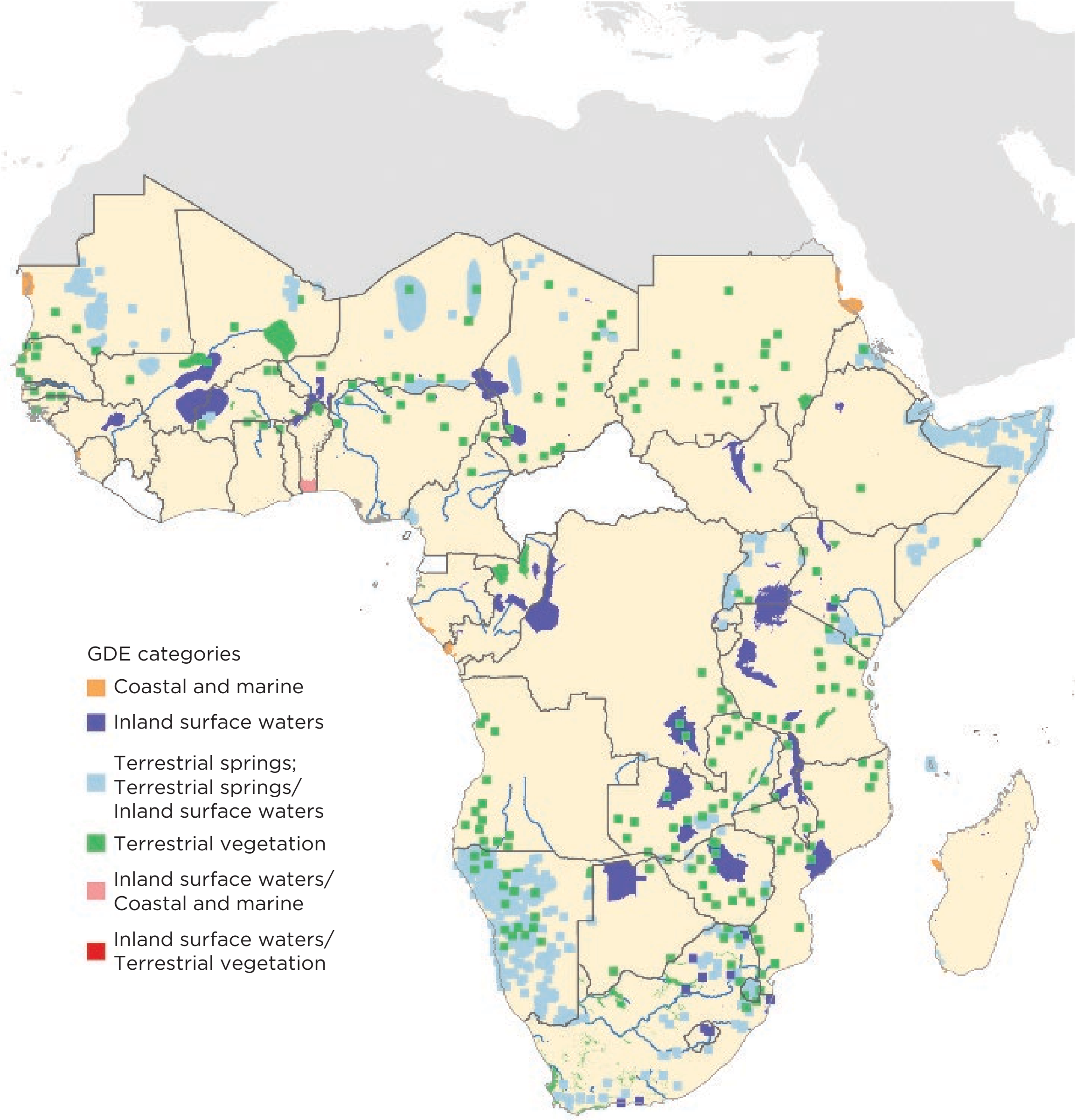
Fauna and flora provide goods and services such as food, medication, energy, or timber for construction, which are vital for human development. The absence of healthy ecosystems and natural environments can have profound and devastating consequences. The COVID-19 pandemic showed how the disruption of ecosystems can lead to zoonotic viral diseases that spill over to humans with staggering health, economic, and societal costs.

Groundwater sustains a broad range of ecosystems – groundwater-dependent ecosystems (GDEs) play important roles across their diversity. GDEs are ecosystems that 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 ecosystem services. Some ecosystems are supported entirely by groundwater while others also receive water from different sources. Groundwater is critical to certain species because it provides the needed water chemistry or stable water temperature. While some GDEs are well identified such as some lakes or oases, some others are less obvious, notably onshore GDE such as mangroves, sustained jointly by seawater, rainfall, surface water, and groundwater. Mangroves provide habitat to several aquatic and semi-aquatic species and deliver important ecosystem services such as carbon sequestration and methane reduction, water filtration, and protection against coastal erosion and storm surge. Another example is the contribution of groundwater to the fishery resource in coastal areas: Santos et al. (2021) demonstrated that submarine groundwater discharge of coastal aquifers is an essential part of the coastal nutrient budgets, mainly nitrogen.

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 key net carbon sink role GDEs play. 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. The role played by GDEs in the livelihoods of some of the most vulnerable populations in Sub-Saharan Africa such as pastoralists in the case of the Sahel and through key mechanisms in plants such as the hydraulic lift has also been more recognized.[1]

GDEs are poorly understood, and the groundwater requirements to meet their ecological functions are rarely considered in land-use policies and planning. Still, local knowledge about those GDEs is not reflected through systematic identification and mapping at scale, particularly

Map A.1. Groundwater Dependent Ecosystems in Sub-Saharan Africa, by Category

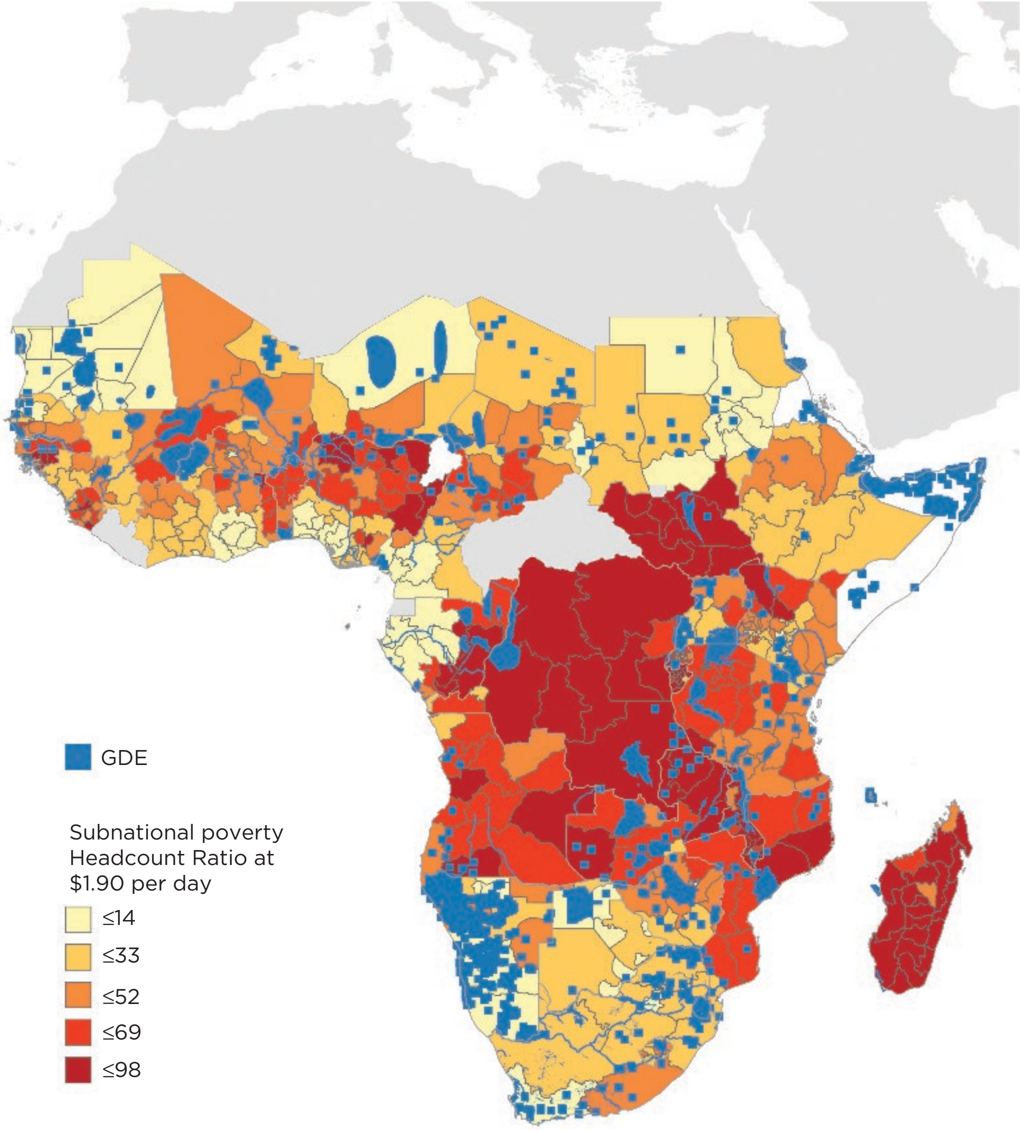


Source: World Bank GDE database and World Bank's Global Subnational Atlas of Poverty.

in developing countries. This lack of information is problematic as GDEs, particularly those in dryland areas, are most exposed to small variations in the groundwater levels that can threaten their very existence.

A new systematic World Bank database of GDEs in Sub-Saharan Africa shows their diversity, and importance to people living in situations of poverty. Compiled using a wide range of sources

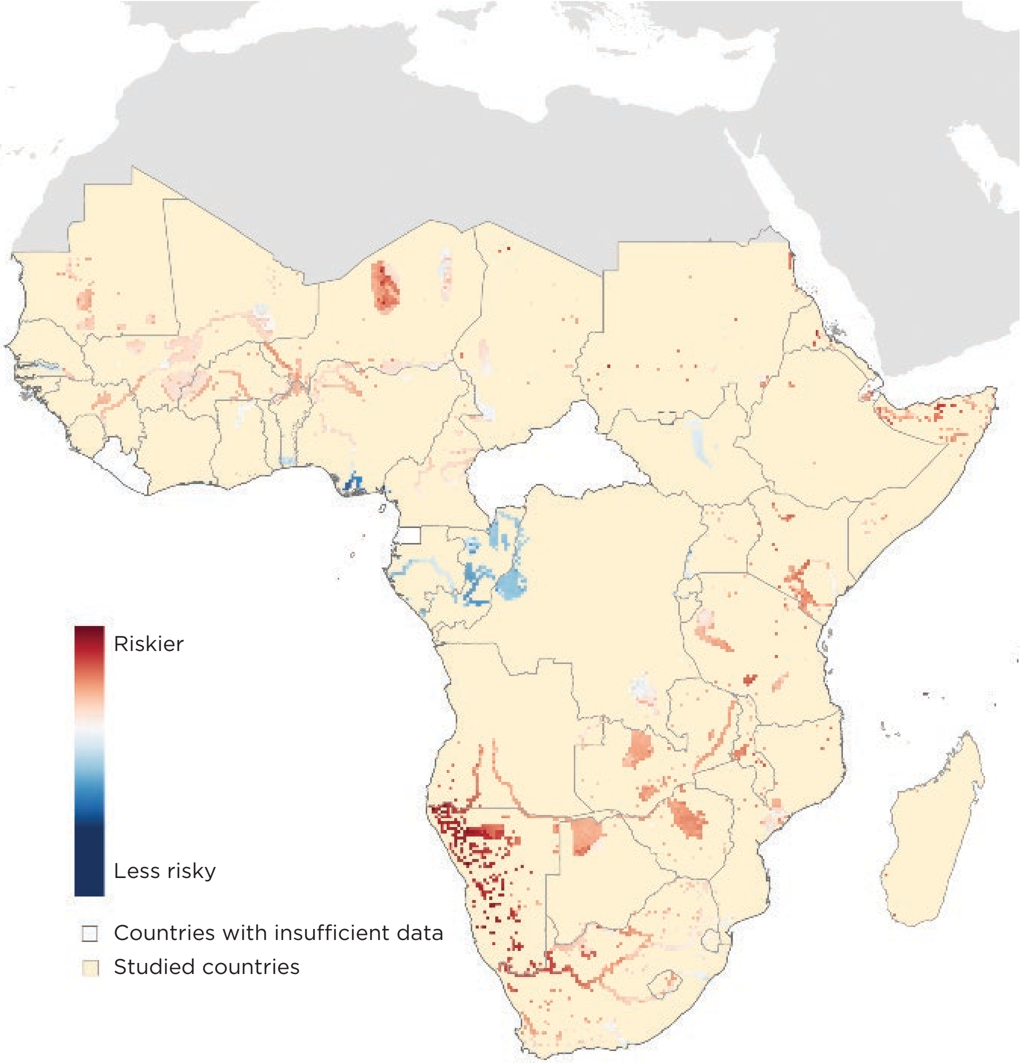
Map A.2. GDEs are Critical to Livelihoods in Some of the Poorest Areas, at the Crossroads of Crucial Rural Socio-Economic Dynamics



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

reflecting local and academic knowledge as well as through country consultations, the database identified over 200 GDEs across four main geographic types (inland surface waters, coastal and marine ecosystems, terrestrial springs and oases, and terrestrial vegetation). Map A.1 illustrates the localization of those GDEs (per sub-categories) across the region. This new database helps bring GDEs into focus but will require further expansion to better reflect all GDEs in the region and contribute to their monitoring. As seen in Map A.2 groundwater-dependent ecosystems are critical to rural communities, sustaining the livelihoods of many households living in situation of poverty, particularly in dryland regions.

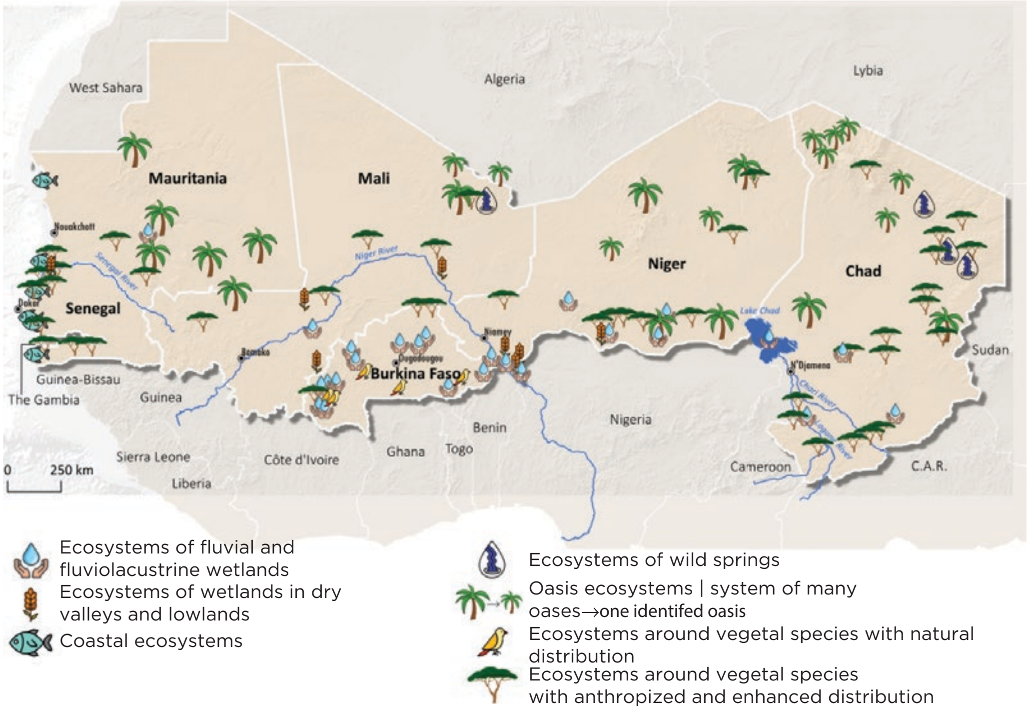
Map A.3. Localization of Groundwater-Dependent Ecosystems at Risk of Overexploitation from Unfettered Solar Pumping



Source: Zuffinetti and Meunier (2023), for this report.

But a lack of knowledge and awareness about GDEs expose them to multiple risks – including through interventions inadvertently leading to maladaptation. The sensitivity of GDEs to even small changes in the water table put them under threat of an increased uncontrolled use of groundwater, particularly for irrigated agriculture – the main consuming sector. A comprehensive data analysis to estimate the risk of overexploitation posed by an uncontrolled expansion of photovoltaic pumping in Sub-Saharan Africa shows that most GDEs, and by extension the people and biodiversity that rely on them, are indeed at risk (Map A.3).[2] Beyond the needed policies and institutions, energy and other integrated development projects need to consider the implications for groundwater use and possible externalities.

Map A.4. Localization of Groundwater-Dependent Ecosystems Per Sub-Category in the Western and Central Sahel

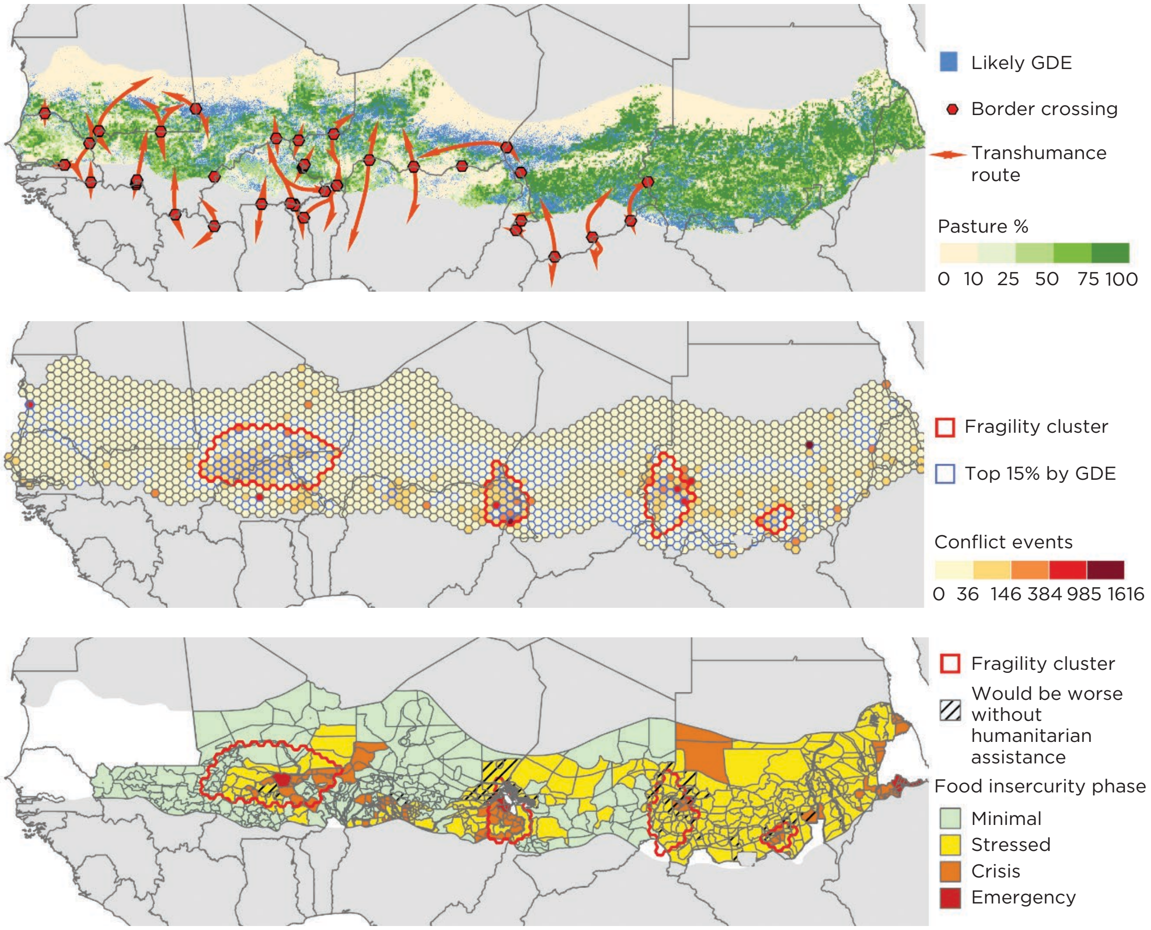


Spotlight on the Sahel

In the Sahel region, as for most dry land where water resources are mostly underground, groundwater-dependent ecosystems (GDEs) are essential lifelines for communities, around which a multitude of social interactions and economic activities develop. Healthy ecosystems are key for livelihoods and economies. GDEs provide direct goods and services to humans including fish, livestock, plants, medicines, timber, and water storage and purification. Indirect benefits to human well-being derive from sustaining biodiversity, habitat, and landscapes for social, cultural, aesthetic, ethical, and economic reasons. GDEs are also fundamental to the survival of various protected species and figure prominently in sites covered by the RAMSAR Convention on Wetlands

In regions with large section of drylands, such countries of the Sahel, groundwater underpins all rural livelihoods. Mapping of Sahel's GDEs conducted in 2020 and 2021 identified 123 GDEs in Western and Central Sahel (Rambhunjun et al., upcoming). The map below (map A.4) locates some of them across the six Sahelian countries but many more need identification and description.

Map A.5. 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.

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 A.5). 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.

Notes

1. The hydraulic lift is the process through which some deep-rooted plants take in water from lower, wetter soil layers and exude that water into upper, drier soil layers. This mechanism, which is 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 to dryland areas.
2. 50 percent of GDEs with a high risk of overexploitation rely on local shallow aquifers. Close to 25 percent of them rely on major alluvial aquifers (such as northern Botswana and Niger). See Zuffinetti and Meunier (2023) – background paper prepared for this report.

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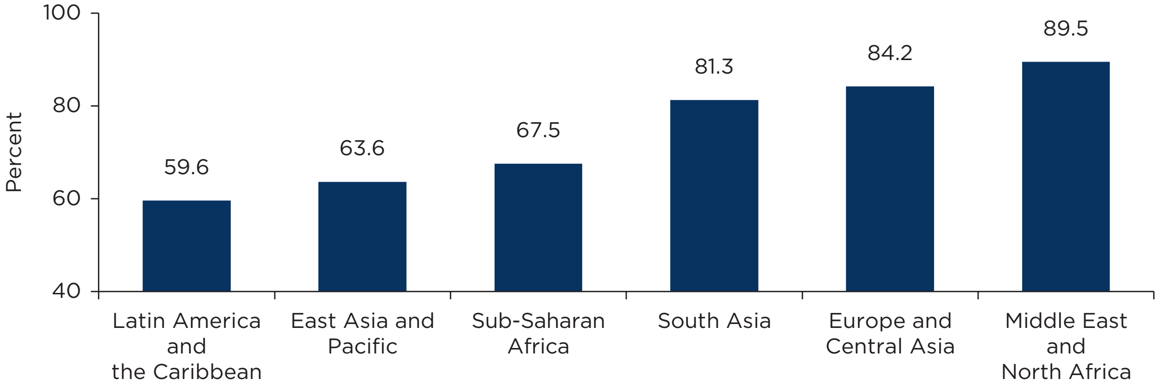
Annex 4: Groundwater and the Cities[1]

Why Does Groundwater Matter for Sustainable Urban Water Supply?

Water is an indispensable resource for urban life. From domestic uses to commercial and industrial uses, and to local community uses to support, for example, firefighting, landscaping, and public spaces, almost all activities taking place in cities need water. Not only within cities, but urban dwellers rely heavily on water consumed outside the city limits to meet their needs, such as food and energy (Hoekstra, Buurman, and van Ginkel 2018). Thus, at times of unprecedented urbanization coupled with increasingly severe dry shocks, the importance of securing resources for urban water supply, as well as to support urban populations, is ever growing.

Although thinking about water sources often brings to mind surface water such as rivers and reservoirs, groundwater, in fact, provides nearly 50 percent of urban water supply globally (IAH 2015). An analysis of 220 large cities from non-high-income countries also reveal that groundwater sources account for, on average, 60 to 90 percent of their water intake points across regions (figure A4.1). In the fast urbanizing developing world, the presence of water-yielding aquifers is particularly important because self-supplied water wells and boreholes provide a viable option for the poor as well as local businesses in the urban fringe to secure water supplies at a lower cost (Foster et al. 2020; Healy et al. 2020). Besides, relative to surface

Figure A4.1. Average Share of Groundwater Sources Out of Total Water Intake Points, Circa 2014



Source: World Bank calculation using data from The Nature Conservancy and McDonald (2016).

water, groundwater is naturally of better quality as it is protected below the surface (Foster and Vairavamoorthy 2013) and is more resilient to precipitation variability owing to its buffer capacity (Zaveri et al. 2021). Hence, so long as aquifers in and around cities are properly managed and protected, groundwater is well positioned for urban water security especially at times of water stress.

However, rapid urban expansions in developing countries in recent years have been raising concerns regarding groundwater resources, which can have a variety of repercussions down the road. While one would expect rapid sprawl to occur on urban margins where private access to aquifers may be feasible, such patterns of growth are likely to be a threat to groundwater depletion and degradation due to inadequate quantity and quality controls – typical of developing countries. A heavy reliance on private self-supply, without increasing both the demand and willingness to pay for networked water supply and sanitation (WSS) services, can further impede the expansion of the formal network, which in turn, can damage public health and the prospect of economic development, not to mention the natural environment. Haphazard urban encroachment on productive agricultural land can also create competition between new inhabitants and farmers for water as well as land with potential negative implications for food production and related jobs, and ultimately, the broader economy.

This annex provides evidence that urban areas in developing countries have been growing in ways that can exacerbate the aforementioned issues. Drawing on spatially granular land cover classification along with aquifer typology maps, the analysis describes the growing patterns of urban space during the years 1992–2020 for a sample of over 9,000 cities outside high-income countries. For the description of urban sprawl, the analysis builds on the sprawl index developed by Burchfield et al. (2006) and defines a city's peripheries as the total area within one kilometer around the city's boundary in 1992. In the analysis, particular attention is given to cities in Sub-Saharan Africa where groundwater-related concerns have been mushrooming during rapid urbanization in recent years (Foster 2022).

Cities Grew Faster Where Water-Yielding Aquifers are Available

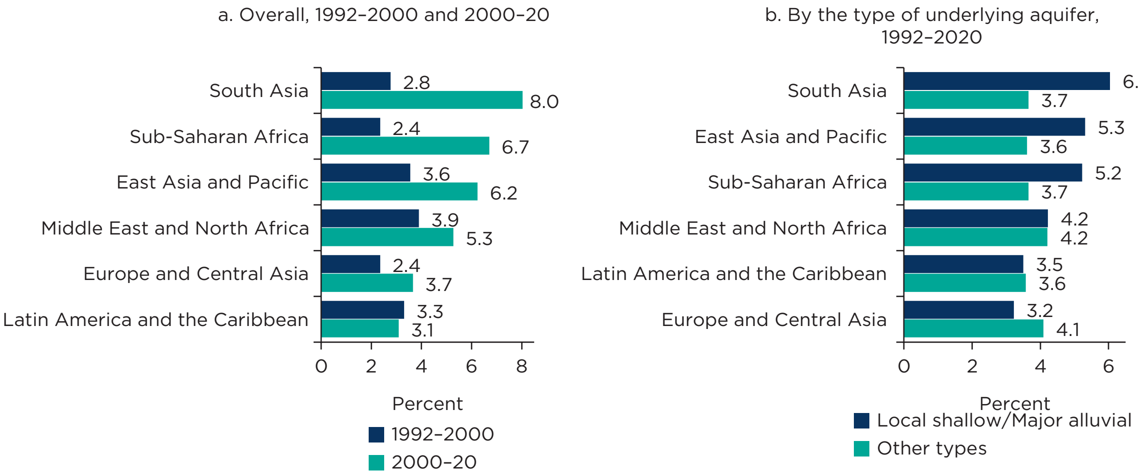
The existence of high-yielding aquifers, such as major alluvial and most of the complex aquifers, in the urban fringe can be an important determinant of shaping cities because it offers significant benefits for both developers and households (Burchfield et al. 2006; Foster 2022). Developers, for example, can save a significant amount of capital expenditure by drilling wells to supply off-grid water networks rather than connecting new developments to a formal network. Private self-supply from groundwater sources can also be an attractive option for households, especially for the poor in the urban fringe, because they not only can access water before formal water supply systems are provided but also can avoid higher tariffs they would need to pay if they were connected to a public service. Hence, the availability of this alternative water-supply option can facilitate urban growth, which is scattered and uncontrolled most of the time.

During 1992–2020, cities across low- and middle-income countries experienced urban spatial expansion at 5.1 percent per annum on average.[2] Such a rapid expansion of urban space is particularly pronounced since the turn of the century, largely driven by cities in South Asia, Sub-Saharan Africa, and East Asia and Pacific, as well as Middle East and Northern Africa to a lesser extent (figure A6.2, panel a).

In the regions experiencing the fastest spatial expansion over the last three decades, cities over local shallow or major alluvial aquifers grew faster, that is, where private self-supply might be possible. In South Asia, for example, cities grew, on average, by six percent per annum over local shallow or major alluvial aquifers, whereas the average growth rate elsewhere was 3.7 percent annually. In East Asia and Pacific and Sub-Saharan Africa, faster urban growth likewise occurred over local shallow or major alluvial aquifers at the average annual growth rate of over five percent. In areas where such types of aquifers are not accessible, urban growth has been slower at a rate of below four percent per year (figure A6.2, panel b).

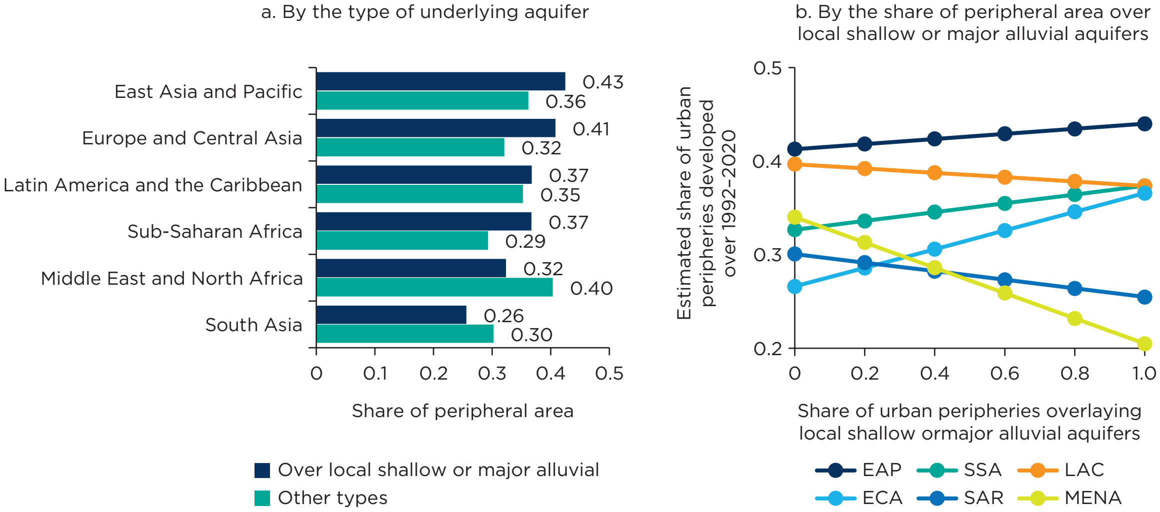
The analysis furthermore shows that in most of the regions, urban peripheries overlaying local shallow or major alluvial aquifers had been developed to a larger extent than elsewhere over 1992–2020. The contrast between the two types of peripheries is the most noticeable in Europe and Central Asia, Sub-Saharan Africa, and East Asia and Pacific, where more or less 40 percent of peri-urban area overlaying local shallow or major alluvial aquifers was converted from natural to built-up land over the last three decades. By contrast, the shares appear to be 7–9 percentage points lower elsewhere in those regions (figure A6.3, panel a). Those regions also exhibit that the wider the urban peripheries that overly local shallow or major alluvial aquifers, the more developed the peripheries are (figure A6.3, panel b). Although this does not necessarily imply causation, it is evident that sprawl has occurred where self-supply from groundwater might be feasible.[3]

Figure A4.2. The Average Annual Growth Rate of Urban Area



Sources: World Bank calculation using data on land cover classification from Copernicus Global Land Service, aquifer typology derived by the Flagship team, and the sample of cities from the Global Human Settlement–Urban Centre Database R2019.

Figure A4.3. Share of Peripheral Area Developed Over 1992–2020



Sources: World Bank calculation using data on land cover classification from Copernicus Global Land Service, aquifer typology derived by the Flagship team, and the sample of cities from the Global Human Settlement–Urban Centre Database R2019.

Note: The boundary of each city's peripheral area is delineated as the total area within one kilometer around the city's boundary in 1992. The figure in panel b is obtained by regressing the share of urban peripheries developed over 1992–2020 on the share of urban peripheries overlaying local shallow or major alluvial aquifers while controlling for the initial population, as well as each city's average level of elevation, average annual temperature, and total annual precipitation. EAP = East Asia and Pacific. ECA = Europe and Central Asia. LAC = Latin America and the Caribbean. MENA = Middle East and Northern Africa. SAR = South Asia. SSA = Sub-Saharan Africa.

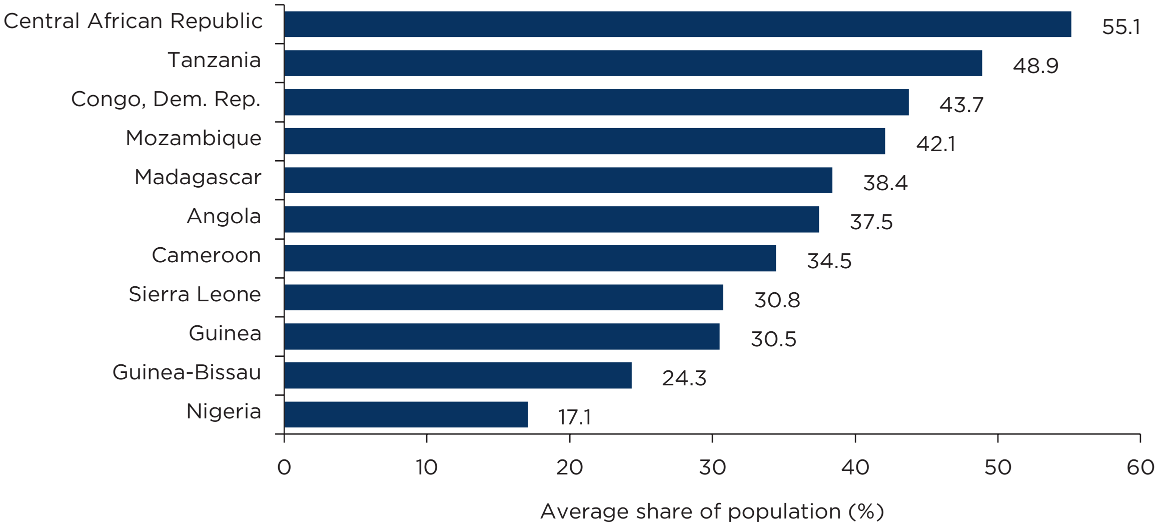
In Sub-Saharan Africa, Many Cities are Growing Fast Over Water-Yielding Aquifers Without Improved Sanitation

In the last decade or so, the reliance on private water wells has proliferated across fast growing cities in, for example, Sub-Saharan Africa (Foster 2022). Successful access to groundwater sources means that lower-income households, particularly those in peri-urban slums, can meet their needs without waiting for a public-supply to be extended. Despite the benefit, it comes at a cost of groundwater contamination and eventually, health hazards because most households rely on shallow water wells that are vulnerable to pollution from in-situ sanitation and other urban waste. Looking at cities overlying local shallow or major alluvial aquifers in select Sub-Saharan African countries, more than 30 percent of the population, except in Guinea-Bissau and Nigeria, are served by in-situ sanitation (figure A6.4). Given that about 30 percent or more urban population in each of these countries appear to rely on groundwater sources for drinking water supply,[4] this result highlights a potentially serious hazard to groundwater quality those people face.

Many Countries Will Likely Face Urban-Rural Competition for Water

Rapidly sprawling cities often meet their demands for scarce land by encroaching on surrounding agricultural land. And new inhabitants meet their water demands by exploiting freshwater,

Figure A4.4. **Average Share of Population Relying on Unimproved Sanitation Across Cities Over Local Shallow or Major Alluvial Aquifers, Circa 2016**



Sources: World Bank calculation based on unimproved sanitation data from Low- and Middle-Income Countries (LMIC) Drinking Water and Sanitation Access and the Flagship team's aquifer typology data applied to city boundaries from the Global Human Settlement–Urban Centre Database R2019.
Note: Unimproved sanitation facilities include pit latrines without slabs, hanging latrines, and bucket latrines.

including groundwater resources. Such encroachment of productive land and exploitation of water resources may cause farmers to be deprived of crucial inputs into agricultural production operations, threatening their livelihoods. Thus, rapid urban sprawl over agricultural land will likely create competition not only among urban dwellers but also between urban and agricultural water users, which will only be intensifying over time due to continued urbanization and climate change (Flörke, Schneider, and McDonald 2018).

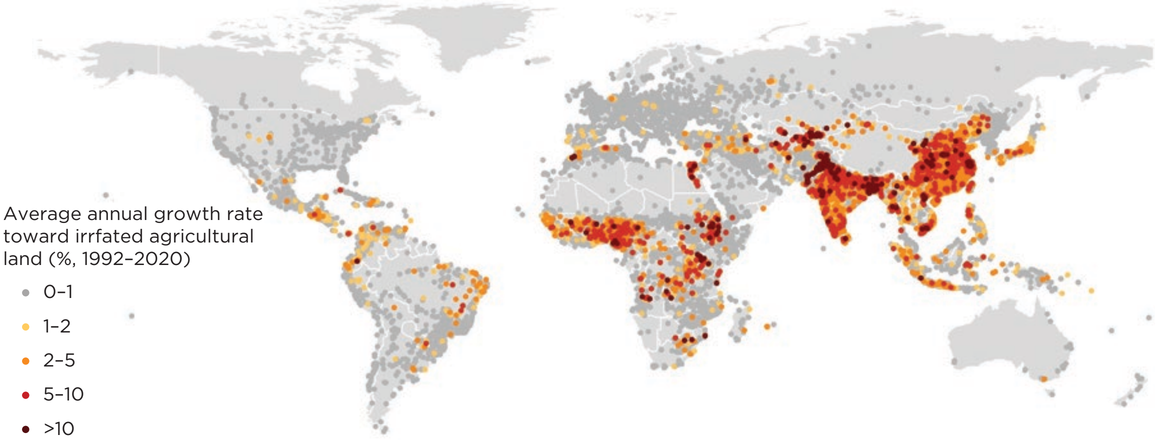
South Asia, Middle East and North Africa, and parts of East Asia appear to be hotspots where competition between urban and agricultural water (both surface water and groundwater) uses is the highest due to rapid urban sprawl toward irrigated agricultural land (map A6.1).

Looking in detail by country, a high level of potential competition is pervasive in all South Asia and some countries in Central Asia, as well as China, Myanmar, and Vietnam in East Asia (figure A6.5, panel a). Even in the central part of Sub-Saharan Africa, where irrigation is limited, there are already signs of competition. (figure A6.5, panel b).

Summary and implications for sustainable urban water supply

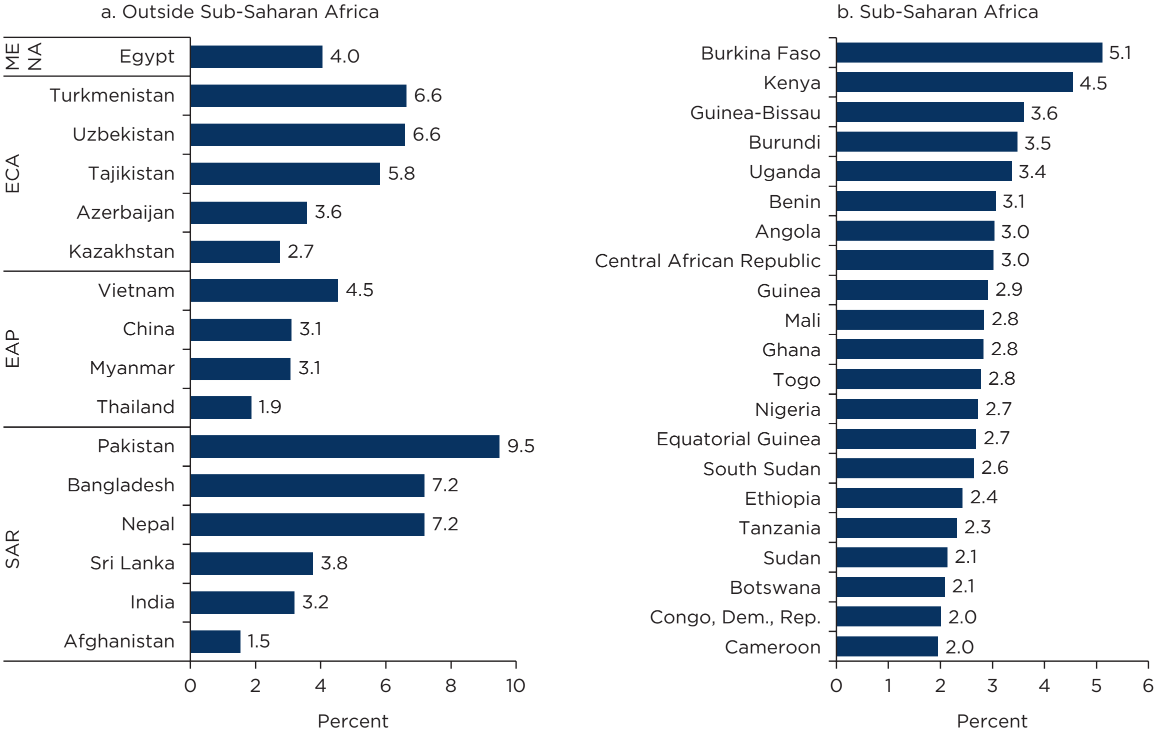
The analysis of over 9,000 cities from developing countries shows that rapid urban expansions in the last three decades have been centered around the areas where private access to groundwater sources might be possible. Many urban dwellers in Sub-Saharan Africa are likely to be severely exposed to groundwater quality hazards as indicated by the share of population using unimproved

Map A6.1. Average Annual Growth Rate of Urban Area Over Irrigated Agricultural Land, 1992–2020



Sources: 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 location of each city is drawn from the European Commission's Global Human Settlement–Urban Centre Database R2019.

Figure A6.5. Average Annual Growth Rate of Urban Area Over Irrigated Agricultural Land, 1992–2020


a. Outside Sub-Saharan Africa

b. Sub-Saharan Africa

Sources: 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 location of each city is drawn from the European Commission's Global Human Settlement–Urban Centre Database R2019.
Note: In both panels, except for Afghanistan and Thailand, the figures show countries with the average annual growth rate of at least 2 percent after rounding. The calculations are based on cities overlying local shallow or major alluvial aquifers.

in-situ sanitation facilities. Although this annex does not assess how many urban dwellers rely on private self-supply from groundwater, these results are in line with existing literature that the resource has become increasingly stressed by overexploitation and contamination (World Bank 2008; Foster 2022; Lapworth et al. 2017). If left unaddressed, the issues might persist for years while compromising human health and undermining the prosperity, livability, and inclusiveness outcomes that urbanization is expected to generate.

The projection of global urban growth suggests that groundwater will likely continue to play a key role in meeting increasing water demands across developing countries (He et al. 2021). Thus, it seems imperative for the governments of these countries to integrate groundwater into their urban water systems and formalize the administration of the resource not only to monitor and control level changes but to safeguard its quality. In the longer term, stimulating latent demands and willingness to pay for formal services among current private well users look critical to increasing revenue collection in utilities, thereby mobilizing new investments in the WSS infrastructure.

Furthermore, an analysis reveals that many cities overlying local shallow or major alluvial aquifers in Sub-Saharan Africa and Asia often encroach on irrigated agricultural land, suggesting potentially harmful competition for groundwater resources between urban dwellers and rural farmers. Carefully managed urbanization, as well as legal and institutional arrangements, can help prevent haphazard sprawl while promoting equitable resource allocations. At the same time, new technologies and strategies to reduce demand and improve efficiency in resources, both for urban and irrigated uses, are urgently needed.

Notes

1. This annex was written by Jane Park with inputs from Pedro Rodriguez Martinez.
2. During the same period, the average annual growth rate of urban area for cities in high-income was 2.3 percent per annum.
3. Although further research is needed to find out the reason behind the declining patterns for South Asia and Middle East and Northern Africa, it is presumed that the existence (or prevalence) of high-yielding aquifers does not matter much for urban expansion in those regions because access to such aquifers is pervasive throughout South Asia while being limited in Middle East and Northern Africa.
4. Calculations based on drinking water sources data from the WHO/UNICEF Joint Monitoring Programme (JMP).

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Annex 5: Groundwater Quality – the Exponential Threats[1]

1. Groundwater Quality – The Difference Between Groundwater and Surface Water

Groundwater quality is affected by a complex natural setting by comparison to surface water and groundwater contamination also has its unique characteristics. Some naturally occurring substances in rocks and soil, such as arsenic, fluoride, manganese, and radionuclides, can accumulate in groundwater and cause widespread concern for public health. Groundwater quality is also affected by complex interactions with human activities, such as irrigation, municipal and industrial development, and mining, which alter the groundwater regime and introduce anthropogenic contaminants into groundwater.

Natural Complexity

The interaction of groundwater with the heterogeneous soil and aquifer environments in which it circulates creates a natural variability in groundwater quality.

Naturally Occurring 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, iron, manganese, radionuclides, and trace metals. Since the 1980s, natural contaminants have been recognized to be more extensive and significant than previously thought.[2]

- ***Arsenic:*** Nearly 108 countries are affected by arsenic contamination in groundwater. More than 230 million people worldwide are estimated to be at risk of arsenic poisoning, including 180 million from Asia.[3] Irrigation with arsenic contaminated groundwater can also directly increase arsenic levels in crops and soils. Long term exposure to arsenic from drinking water and food can cause a wide range of health issues, including cancers, skin lesions, cardiovascular disease and diabetes, negative impacts on cognitive development in utero and early childhood, and increased deaths in young adults.[4]
- ***Fluoride:*** Approximately 180 million people worldwide are potentially affected by fluoride in groundwater, most reside in Asia and Africa.[5] Fluoride at low concentrations has beneficial effects on teeth, but excessive exposure to higher concentrations can lead to adverse effects, ranging from mild dental fluorosis to crippling skeletal fluorosis.[6] Arid and semi-arid regions

are generally more likely to have high fluoride concentrations in groundwater, due to higher pH and alkalinity, enhanced chemical weathering, and longer residence times.[7]

- ***Manganese:*** Together with iron, manganese is naturally present in groundwater. In drinking water manganese may cause health issues, as it is associated with neurotoxicity in humans and animals[8] and impairs the intellectual development of children.[9] However, awareness of its impacts remains low.[10] With increasing knowledge on the health impacts of manganese, its presence in groundwater should be monitored more closely.
- ***Radionuclides:*** Groundwater can contain radioactive elements. Radionuclides occur naturally in many rocks and minerals and are frequently found in groundwater. Uranium is nephrotoxic in that the chronic ingestion of uranium in drinking water can cause kidney malfunction.[11] Radon-222 is formed by the decay of radioactive uranium and can dissolve in water easily and then is released from the water into the air, which can cause lung cancer when inhaled. Radium-226 and radium-228 are also the daughter products of the decay of uranium. They are carcinogenic and can be dissolved in drinking water, then accumulate in bones and other tissues and increase cancer risks.

Interactions with Surface Water

Interactions between groundwater and surface water can impact the quantity and quality of both systems. Therefore, groundwater quality management needs to include assessment and control of surface water contamination and vice versa. These complex surface water and groundwater interactions call for an integrated water quality management approach. The properties of the transition interface between surface water and groundwater (i.e., hyporheic zone) can also significantly influence the transport of pollution. As groundwater supports the baseflows of most rivers, groundwater quality can greatly impact the health of aquatic ecosystems especially during the dry season.

Complexity of Groundwater and Socioeconomic Interactions

Already naturally complex and heterogeneous in character, the introduction of a variety of anthropogenic substances to groundwater systems gives rise to further cocktails of contaminated groundwater.

Agricultural Development and Irrigation

Up to 38 percent of the global irrigated areas are supplied by groundwater.[12] It is estimated that around 30 percent of irrigation water withdrawals forms return flows to recharge groundwater and surface water.[13] Irrigation typically enhances groundwater recharge, which can have negative impacts on groundwater quality.

- ***Application of Fertilizer and Pesticide:*** The massive application of organic and inorganic chemicals in the agricultural sector has resulted in the contamination of both surface water and groundwater. Not all the nitrogen and phosphorus from the applied fertilizer are taken by crops, causing surplus nitrogen stored in soil or leached to groundwater. The vadose zone is an important store of nitrate and can act as a buffer zone to slow nitrate leaching into groundwater.[14,15] Pesticide can reach groundwater directly or indirectly through leaching and runoff. Groundwater depth, soil texture, irrigation and infiltration can significantly impact the movement of pesticide, and pesticide metabolites obtained from the degradation of the original molecule or yet a metabolite, into groundwater. The properties of pesticide itself, such as persistency, solubility and absorption can also influence pesticide movement. Usually, the pesticides that are relatively persistent, highly water soluble, and difficult to be absorbed by soil particles have greater potential to move and pose higher risks to groundwater quality.

- ***Wastewater Irrigation***: The use of wastewater or reclaimed water for irrigation may further deteriorate groundwater quality. Major ions and trace elements, organic contaminants, virus and bacteria, and micro to nano plastic particles contained in wastewater, may infiltrate into shallow groundwater. The high load of salts in wastewater can leach into groundwater and cause salinity. Metals in wastewater may also accumulate in the soil layer and reach shallow groundwater in the long term. Some emerging pollutants in wastewater, such as pharmaceuticals and microplastics from personal care products, can potentially reach shallow groundwater.[16]

Urban and Industrial Development

Urban and industrial development can deteriorate groundwater quality, as it introduces new potential pollution sources. Point source pollution from industrial areas can contaminate soils, enter into surface water and generate pollution plumes in aquifer. Contamination of groundwater in urban and rural areas can occur through many pathways, such as the leakages from landfills, poorly managed sewerage systems and septic tanks, wastewater lagoons, fuel storage tanks, and animal waste. Urban stormwater runoff can infiltrate into soils and recharge groundwater, introducing pollutants at the same time, such as heavy metals, tire- and vehicle-derived chemicals, paints and manufacturing chemicals, as well as pathogenic bacteria and viruses. The release of sewage effluent and poor management of human and animal wastes can induce microbial contaminants into groundwater, increasing the risks of human exposure to waterborne pathogens.

Salinity

Groundwater quality degradation due to salinization is one of the most important challenges limiting the utilization of groundwater. The increased dependence on groundwater to sustain social and economic development is threatened by groundwater salinity issues, especially in developing countries.[17]

- ***Africa:*** Groundwater is the principal source of drinking water in Africa: in Sub-Saharan Africa, around 44 percent of the overall population (for both cities and rural areas) relies on groundwater for drinking. And on average, a quarter of the urban population in in Sub-Saharan Africa relies on groundwater, and in such countries as Nigeria, this reliance rises to close to 60 percent Salinity may be one important factor that restricts the utilization of groundwater in this region.[18] Majority of groundwater samples in Africa have relatively low salinity.[19] The basement rock areas, which supply most of the African rural population with drinking water sources, hold low salinity groundwater resources with the median EC values less than 500 μs/cm. These low salinity groundwater sources can serve as the critical resources to support social and economic development and buffer the potential negative impacts of climate change. However, groundwater salinity may affect water security in arid areas in Africa. High groundwater salinity has been noted in the arid areas in North Africa such as Egypt, Libya, Tunisia, and Algeria, as well as the semi-arid and arid areas with low groundwater recharge environments in Eritrea, Djibouti, Somalia, Botswana, Namibia, Chad, Ethiopia, Senegal, Mauritania, parts of Kenya and Tanzania, and South Africa.

- ***Asia:*** South Asia consumes the largest volume of groundwater resources in the world.[20] Salinity in groundwater affects its suitability for irrigation and drinking water supply. Inland groundwater salinity affects large areas in western and northwestern India and the lower Indus basin in Pakistan. The Indus basin in Pakistan faces growing groundwater depletion, as well as widespread areas of shallow water tables and saline groundwater, leading to the problems of waterlogging and secondary salinization. [21] In the coastal areas, seawater intrusion led to the salinization of the depleted coastal aquifers in the delta areas of the Ganga and Indus Rivers, and the east coast of India. In Southeast Asia and the Pacific region, groundwater serves as a critical source of drinking water[22] yet groundwater salinity widely threatens drinking water security in this region, especially in the coastal areas.[23] Major metropolitan areas located on the coastlines of Vietnam, Thailand, the Philippines, Indonesia and the Pacific Island countries already experience saltwater intrusion and groundwater salinity due to massive groundwater pumping and episodic and persistent droughts.[24,25] Central Asia is significantly impacted by the salinization of soil and groundwater. The huge expansion of irrigation in the 1960-80s had led to salinity and associated waterlogging issues, which hampered the ability of plants to absorb water and thus leaded to declining agricultural production.
- ***Latin America:*** In Latin America, land use changes have led to groundwater salinity in many regions. Conversion of natural woodlands to croplands alters the hydrological balance, groundwater recharge, and the salinity of soil and groundwater. It has been found that large-scale deforestation for agriculture during the past century substantially increased groundwater recharge in some areas in Argentina. The increased recharge and deep soil moisture drainage led to the increased leaching of sulfate and chloride ions from the shallow vadose zone into groundwater, causing the salinization of groundwater. [26] The conversion of natural grasslands and pastures into croplands could also cause similar groundwater salinity issues in the semi-arid areas of central Argentina.[27] In the coastal regions, groundwater salinity due to seawater intrusion is also widely found in the coastal aquifers in Latin American countries, such as Brazil,[28] Peru,[29] and Mexico.[30]

Mining

Mining significantly influences groundwater quality, long after mine closure. Acid mine drainage (AMD) is considered one of the main causes of groundwater contamination in many countries with active or abandoned mining activities. Mining activities expose sulfur-bearing minerals to air and water, which are then oxidized and release a large amount of sulfuric acid and dissolved toxic metals to form highly acidic wastewater. AMD is highly acidic, which subsequently promotes the releasing of a wide range of metals. Thus, AMD contains high concentrations of toxic heavy metals. The generation of AMD may continue for centuries, even after mines are abandoned. Besides the acid drainage, groundwater can be contaminated by leakages from tailing dams, and the toxic chemicals for mine material processing, such as cyanide, reagents and solvents. Changes in flow regime during and after mining also impact groundwater quality. Extensive aquifer dewatering for mining can change groundwater stratification. After mine closure, dewatering ceases and the groundwater table starts to rise. The flooding of mine sites further changes groundwater quality due to the dissolution and flushing of oxidation products and mine waters.

Spatial and Temporal Scales

Natural and human induced groundwater contamination occur at different scales. Groundwater quality is influenced by many factors, such as regional scale climate factors and local scale heterogenous aquifer properties. One of the key challenges of groundwater quality management is to accommodate the multiple spatial scales of system processes and interests.[31] Similarly, unlike surface water processes, groundwater system processes occur at multiple temporal scales, with travel times ranging from days to millennia. The substantial time lags between cause-and-effect lead to difficulties in detecting and understanding groundwater contamination issues. The time lags between action and results also influence the management and remediation of groundwater quality. Remedial actions may take decades or longer to make noticeable changes. Remediation of deep groundwater contamination can be especially challenging as deep groundwater has long travel times and may require millennia to flush.

2. Groundwater Quality Management

Managing groundwater quality issues requires approaches distinct to those for surface water. Surface water pollution issues are more visible, can be detected more easily and are more readily remediated. However, groundwater pollution issues are invisible, may remain undetected for decades, and require a much longer time to remediate.

Uncertainty

Limited groundwater quality monitoring makes groundwater management challenging and increases the uncertainty. Well samplings provide “point-data”, which induce uncertainties in understanding the spatial and vertical extent of groundwater quality problems. Thus, groundwater monitoring networks should suit the local groundwater environment and the type of contaminant to be monitored. Depth-dependent sampling is needed to capture contaminate distribution at various depths. Monitoring frequency needs to be periodically reviewed to understand the ongoing risks of groundwater contamination and determine the timescale of water quality changes.

Uncertainty is related to the complex natural and socioeconomic processes. No natural or socioeconomic systems can be perfectly characterized, especially the groundwater quality system which is affected by both natural and human settings. The natural hydrogeological setting is heterogenous, and naturally occurring contaminants are distributed unevenly. The interactions between groundwater and surface water further increase the complexity and uncertainty, which calls for integrated management of both surface water and groundwater quality. Many human activities draw anthropogenic contaminants into groundwater. The lack of detailed understanding of both natural groundwater systems and related human activities imposes uncertainties into groundwater quality management.

Uncertainty is also linked with the spatial and temporal scales of quality issues. Groundwater quality issues and related impact factors occur at different spatial scales. Assessments and modeling tools usually face challenges to accommodate multiple spatial scales of issues. The issues and impact factors that are dominant at one spatial scale may become less important at another scale. Upscaling and downscaling information at various scales can induce uncertainties. Multiple temporal scales also induce difficulties and uncertainties to understand and manage groundwater quality issues.

Groundwater Quality Management with Uncertainty

Uncertainty is embedded in all aspects of groundwater quality management. The improvement of groundwater quality monitoring network with well designed, practical monitoring plans can help better understand groundwater quality issues and the associated uncertainty in data.[32] Numerical models provide powerful tools to understand the complex behaviors and responses of groundwater quality to natural and human influences. Although uncertainty is inherent in model simulation due imperfect data and knowledge, models can still provide opportunities to explore uncertainties in groundwater quality management and communicate these uncertainties to decision makers and stakeholders. The policies, actions and plans on groundwater quality management should be periodically reviewed and adjusted to cope with emerging challenges and uncertainties.

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Annex 6: Groundwater Policy and Management Instruments – Will We Run out of Groundwater if We Do Not Get Them Right?[1]

Groundwater is fundamentally plagued by its common-pool resource character. This renders it inherently vulnerable to the so-called 'tragedy of the commons' in which stakeholders act in their own short-term self-interest rather than taking long-term communal best interests into account. The common-pool nature of groundwater implies *de-facto* open access (resource is said non-excludable), which is great from an equitable water access point of view, but complicates regulation of use, especially when dealing with high numbers of users across large areas[2].

Groundwater policy objectives closely link to those of climate adaptation, environment and other land and water resources. While groundwater plays a fundamental role in supporting environmental and climate goals, it is often an afterthought when devising useful adaptation and management solutions. It is critical to get groundwater visible in climate change, environmental and land use policies.

Getting groundwater policies and management right is more critical in dry rural populous areas, large cities, and isolated small island states. Around 70% of groundwater globally goes into irrigated agriculture and even more in arid- and semi-arid regions, supporting livelihoods of billions of smallholder farmers. The fact that these population groups are the most vulnerable to climate shocks, natural disasters, and economic and socio-political instabilities implies the need for prioritized investments and policy support in these regions. In low-maturity areas such as Sub-Saharan Africa with vast poor rural populations, which still lack economic access to groundwater, setting the right foundations of an institutional and regulatory framework is essential. In high-maturity settings like South Asia, the Middle East and Northern Africa, which rely heavily on groundwater for agriculture, strengthen groundwater governance is needed in parallel to measures outside the water sector. Groundwater dependence is growing in most cities around the world, while management tools are lacking, notably when it comes to preserving its quality. Finally, small island states are a category of regions, which struggle with sustainable groundwater use as their often-primary perennial water source. They also need dedicated attention, especially considering their vulnerability to climate change and sea-level rise.

There needs to be a congruence between local and national approaches - and social inclusion. Groundwater policies emanate from national governments, while local regulations may enhance adapting management paradigms to specific contexts and institutions. Paying close attention to these linkages, and ensuring coherence across hierarchical levels of governance is of utmost importance, especially when local management initiatives are implemented. Importantly, farmers and city dwellers are typically not homogeneous stakeholder groups, entailing the need for contextualized, socio-economic, gender-sensitive and compensatory tools, like credits, market access, and training, enabling sustainable access to groundwater benefits for the vulnerable groups.

Subsidies and other external indirect drivers for groundwater use may overrule traditional regulations. Government subsidies (notably in the energy sector) and other economic/market incentives (e.g., solar pumping), often implemented outside the water sector, are powerful tools that may support or distort groundwater-centered regulation mechanisms, like licenses and quotas. Closer analysis of nexus issues and impacts of subsidies are key to understanding the impacts of groundwater-specific regulations and the development of the groundwater sector.

Solving one issue may create a new one – green may not be good for groundwater. An example of possibly distorting subsidies is the support to solar pumping.[3] While the technologies may support a greener, more renewable energy supply, which may have other benefits, like less burden on government subsidies for electricity, and reducing health impacts from use of diesel for pumping, there is little evidence that groundwater pumping will be controlled under such solar-pumping schemes.[4] Solar pumping systems as well as solar power buy-back schemes require right policy and institutions to cope with maladaptation risks.

Policies must adapt to the aquifer type, the state of groundwater development, the management capacity and the socio-economic and climatic conditions. What works in one region may not work in another. Policies that may have worked previously may no longer be fit for purpose. An example is the subsidies that were originally put in place to enhance farmer adoption of private smallholder irrigation schemes in Pakistan, after public boreholes were put in place to enhance drainage and reduce water logging and salinity issues in the canal systems especially Punjab Province in the 1960s and 70s. Similarly, existing subsidies to groundwater-based irrigation may no longer make sense across India. New policies are needed.

Local management does not work in major alluvial aquifers – context matters. The aquifer typology developed in this report serves to highlight key fundamental aspects of the linkage between the inherent aquifer type and potential management instruments. An important lesson is that while local 'self-regulation' of groundwater in local shallow aquifers may have a proven scope, if certain conditions apply (Table A8.1) the likelihood of successfully applying local management approaches in major alluvial aquifers may be small. A critical difference is the larger number of stakeholders per aquifer and the diffuse and slow evidence of success of implementing common rules.

Information, knowledge, and communication systems are prerequisites for good implementation of groundwater policy and management instruments – the same goes for participation and capacity. Designing policies and assessing their impacts require data on the aquifer systems as well as on the users and their interactions with groundwater, directly, or indirectly. Information should be openly available and shared on public platforms. Basing policies on involvement and understanding of stakeholders is key to rolling out measures that will resonate and encourage cooperation on common good goals. Dialogue with government to ensure that the relevant institutions have adequate resources, including skills and budgets, is needed.

Table A8.1. Key Groundwater Policy and Management Instruments

No.	Instrument	Implementation conditions	Advantages	Limitations/Risks
1.	**Transboundary aquifer cooperation**[5]	• Willingness among aquifer-sharing states to enter into water cooperation to address common groundwater issues and seize joint development opportunities • Funding sources available to set up cooperation mechanisms • Hydro-diplomacy	• Can address regional development issues, like population growth, migration, increasing water demand, environmental degradation, climate change • Enhances regional integration • Can realize joint infrastructure projects, economic opportunities, and cross-sectoral cooperation • Enhances opportunities for conjunctive management of transboundary surface water and groundwater • Strengthens border regions	• Investments are inevitably more difficult and involve more transaction costs in the short term, but may defer costs in the longer term • Lack of human capacity and availability, monitoring, sharing, and harmonization of data • Lack of social and gender integration and representation of local government
2.	**Licenses and fees**[6],[7]	• Knowledge of the resource, type of use, withdrawals, functions of costs and marginal income of users, elasticity of water demand for different uses • Effective implementing/ enforcing power • Social sensitivity of regulatory power • Legal control of well drilling • Clear conditions, e.g., duration of licenses	• Incentive for a better valuation of the resource • Incentive for reducing demand • Can be graduated to curb high-end use	• Moderate/high transaction costs • Uncertainty on the effects of a fee and the achievement of environmental objectives • Difficult to adjusts when number of users and demands increase, or due to climate change • Fee collection often inefficient (low human resource capacity, tampering of water meters, reluctance of collectors due to physical access restrictions, threats, etc.)

Continued

Table A8.1. Continued

No.	Instrument	Implementation conditions	Advantages	Limitations/Risks
3.	**Quotas**[8]	- Knowledge of the resource and withdrawals - Effective implementing power - Social sensitivity of regulatory power	- Effective ad-hoc tool (rationing) in emergency/drought situations - Environmental objectives set a priori[9] - Can be modified periodically (e.g., annually)[10] - Relatively low transaction costs	- No incentive for users for water savings beyond the quota, but possibility to use differentiated quotas to address equity issues - Barrier to entry for new users
4.	**Formal groundwater markets**[11]	- Knowledge of the aquifer/groundwater resource unit subjected to market(s) and withdrawals (through continuous monitoring and modelling) - Legally well-defined tradeable water rights and market participants - Effective implementing power - Technical feasibility and exchange of quotas at moderate costs (physically exchangeable volumes)	- Environmental objectives set a priori - Incentive for a better valuation of the resource - Better economic optimization of the use of groundwater - Equity and environmental sustainability can be addressed through various means (e.g., off-sets, collaborative planning, innovative metering/monitoring, conflict management)	- Issue of fairness relating to the allocation of rights - Expensive to set up (water networks, administrative costs, etc.)
5.	**Informal groundwater markets**[12]	**Rural informal markets**[13]: - Local networks among users (mostly smallholder farmers) enabling a market of groundwater services from existing irrigation wells	- Marginal farmers without irrigation wells have access to productive water - Markets adopted where little formal regulations and markets exist - Drilling costs are reduced, and fragmented landholdings can be serviced from fewer wells - Urban dwellers unserved by public water supply have access to water	- Benefits both buyers and sellers, but water-buying farmers may have poorer bargaining power, receiving relatively lower benefits - May undermine top-down incentive policies to reduce water demand[15]

Continued

Table A8.1. Continued

No.	Instrument	Implementation conditions	Advantages	Limitations/Risks
		• Water rights manifested through land rights and well possession. **Urban informal markets**[14]**:** • Private vendors outside public water supply providing water services to unserved communities		• Targeted poor consumers have little power to exert pressure on suppliers in terms of standards of service, water quality, and price • Urban groundwater markets may increase water scarcity and insecurity in peri-urban areas[16]
6.	**Subsidies and economic incentives promoting groundwater irrigation**[17]	• Government policies to enhance irrigated farming, e.g., through reduced prices for well drilling, solar panels, fertilizer and seed inputs, credits, and often free electricity supply for agricultural groundwater pumping • Government guaranteed favorable minimum prices for crop purchase by state procurement agencies • Government subsidies to enhance micro-irrigation technologies	• Subsidies are usually effective due to strong economic incentives for farmers • As a result, groundwater irrigation surpassed surface water irrigation in India in the 1970s • Crop production in India increased at about 3.6% annually since 2011 • India achieved a significant fall in the proportion of undernourished population, from around 24% in 1990-92 to 15% in 2014-16 • Moreover, India emerged as a major agricultural exporter of several key commodities • As such, irrigation access and low food prices, favored by subsidies, has significantly increased food security and economic growth and reduced poverty	• Despite improved impacts in early phases, there is increased inequality and slow economic growth in later stages due to gradual groundwater depletion • Subsides discourage efficient use of resources (groundwater and fertilizers) with resultant groundwater depletion and contamination • Subsidies tend to create path-dependence and strong political lobby from favored clients, making them 'sticky' • Subsidies strain public budgets in the food and energy sectors • Groundwater irrigation expansion in South Asia is increasingly happening in arsenic hazard areas, increasing risk of double-exposure – from water and food, with ramification for food trade[18]

Continued

Table A8.1. Continued

No.	Instrument	Implementation conditions	Advantages	Limitations/Risks
7.	**Formal regulations on behavior to reduce groundwater use**	• Government decrees on drilling, crops, cropping methods, irrigation/irrigation methods[19]	• Relatively easy to implement, can be directed towards vulnerable areas in risk of groundwater depletion • Easy to understand for users, though training and extension services may be required to facilitate transition, uptake, and compliance • Can be associated with fines or awards for adherence or non-adherence	• Difficult to enforce. Monitoring of adherence necessary • Penalties and significant economic consequences for violators or adequate payment/rewards for lawful behavior required • Can be circumvented by politically well-connected parties • Bans may not be economically optimal • Difficult to verify their effectiveness
8.	**Collective management and aquifer[20] contracts[21]**	• The eight principles of Ostrom[22] • Works best in local/shallow aquifers • Knowledge of the resource base and withdrawals/cropped area • Appropriate formal legal framework and empowerment for local water management in place[23] • Joint awareness of (the risk of) overexploitation • Cultural homogeneity and acceptance of common informal rules • Self-governance, including regular self-monitoring and evaluation by users	• Positive impacts on resource quickly discernible • Local enforcement easy through simple social/behavioral regulations • Builds on and strengthens social capital of users and stakeholders • Socially sustainable, acceptable, and adaptable instrument • Can be promoted through local champions • Facilitator for the implementation and integration of other tools (surface water/water quality protection/health, energy, livelihoods, etc.) • Can be facilitated by external support and capacity development (water budget tools, learning, social organization, games)	• Many prerequisites and tedious for successful implementation and institutional anchoring • Enabled through more inclusion/representation in decision making at national and sub-national levels • May be challenged under social and climate change • Difficult to scale out, each case unique • May work better in local/shallow aquifers • Aquifer contracts between government and aquifer stakeholders challenged by engrained institutional and social relations and deficiencies in governance • Local rules may be at odds with national groundwater irrigation policies and subsidies

Continued

Table A8.1. Continued

No.	Instrument	Implementation conditions	Advantages	Limitations/Risks
9.	**Groundwater storage and supply options**[24]	- Surface/rainwater or other water sources for retention and recharge available - Regulation of access to source water and recharged water in place - Subsurface storage space available - Technical, implementation and management capacity	- Important climate change adaptation measures (flood and drought management, seawater intrusion suppression) - Co-benefits, in terms of environmental flows, biodiversity gains, natural water purification - Little land footprint - Application flexibility (approaches span from small informal/traditional to large complex schemes) - More cost-effective, especially the less-engineered and more nature-based approaches - Incremental implementation/ expansion possible	- Risk of groundwater flooding - Risk of adverse water quality changes - Risk of increased water scarcity if not combined with water demand management - Distributional risks (spatially and socially) need concerted attention - Informed and planned approach essential, especially for complex urban and coastal schemes
10.	**Conjunctive groundwater management**[25]	- A new water storage paradigm[26] - A comprehensive water supply and storage plan for a catchment or aquifer - Integration with a disaster risk reduction and climate resilience strategy - Mapping new water sources, including desalination, water transfer and wastewater - Mapping of existing water storage and new storage options	- Combinations of water storage and supply options working conjunctively can enhance benefits and reduce flood and drought vulnerability - Improved water security through diversification of water sources - Conjunctive land and water management across: up- and downstream catchments, multiple schemes, green and grey infrastructure, sectors, demand and supply objectives	- Data gaps and large uncertainty in cost estimation, scenario predictions and identification of best options - Risk aversiveness of investors - Social and environmental safeguards need to be put in place - Intensive participation of local land owners essential - Cross-sectoral cooperation critical - Better aquifer and groundwater assessments needed

Continued

Table A8.1. Continued

No.	Instrument	Implementation conditions	Advantages	Limitations/Risks
11.	**Groundwater quality protection**[27]	• Political priority/ budget • Policies based on a precautionary and preventative approach • Proper legal framework • Institutional strengthening • Public awareness • Groundwater and environmental monitoring	• Addressing groundwater pollution early (or even better preventing it), saves public funds and protects human and environmental health • International regulations based on increasing knowledge of emerging contaminants, health effects, prevention, and remedial action • More awareness of the link between groundwater contamination and ecosystem and biodiversity impacts	• Public pressure to deal with groundwater contamination generally low • Legacy pollution with poor liability hard to tackle • Diffuse contamination (agricultural and geogenic) also more intractable • Vulnerable communities disproportionately affected by poor groundwater quality • More powerful individuals, firms and bigger polluters can lobby for circumventing regulations

Groundwater quality impairment equals groundwater depletion. While focus globally is currently on groundwater depletion as the key threat to groundwater, an impending groundwater quality crisis is still to manifest itself in a broader groundwater sustainability discourse. What is critical in this regard is the slow manifestation of contamination in groundwater and the difficulty in addressing such water quality and associated environmental and human health aspects. The retardation is linked to: 1. The slow movement and spread of contaminants to and in aquifer systems; 2. the sparse and weak monitoring of groundwater quality; 3. the general perception that groundwater is of better (inherent) quality than surface water; and 4. the increased impairment of groundwater from a growing multitude of threats, such as an increasing number of human chemicals used in agriculture, in the industry, in the health sector or resulting from urban waste, or the seawater intrusion in depleted coastal aquifers, or from deep inherently more mineralized groundwater increasingly tapped into. Groundwater can no longer be assumed to be of pristine and good quality. Increasing groundwater degradation in effect equates with groundwater depletion, and treating groundwater and polluted aquifers, which may release contaminants for long periods, is disproportionately costly and time-consuming.

Table A8.2. Key Types of Groundwater Policy and Management Instruments and their Relevance Per Aquifer Types, in High Maturity Use Settings[28]

Aquifer types and key instruments		Local/ shallow	Alluvial	Complex	Karstic
Top-down	Transboundary aquifer cooperation	+	+++	++	++
	Licenses and fees	---	+++	++	++
	Quotas	---	+++	++	++
	Water markets	++ (informal)	+++ (formal)	++ (informal)	---
	Subsidies and economic incentives promoting groundwater irrigation	+++	++	+++	+
	Formal regulations on behavior to reduce groundwater use	+++	++	+++	+
	Collective management and aquifer contracts	+++	---	++	---
	Groundwater storage and supply options	+++	+++	++	+
	Conjunctive groundwater management	+++	+++	+++	++
Bottom-up	Groundwater quality protection	+++	+++	+++	+++

Where and When Will We Run Out of Groundwater?

This question, reflecting what happens if we do not get the management and policies right, is best answered by considering aquifers in terms of the renewable/exploitable part of the aquifer as a simplified approximation of aquifer systems.[29]

The exploitable part of an aquifer experiences ongoing renewal and so the wholesale 'running out' of groundwater is not a realistic scenario. However, a likely scenario is that the groundwater level reaches a depth when it is no longer economically viable to continue extracting groundwater due to disproportionate increases in costs associated with deepening wells and the increasing use of energy for pumping. When we use more groundwater than is being replenished through recharge, we are effectively mining groundwater and, if we know the hydraulic characteristics and usage volumes, we can make a reasonable estimate of how long it will last, based on current figures of economically viable abstraction infrastructure depths. For shallow aquifers that effectively only contains renewable groundwater and where the base of the aquifer can be reached by economically viable abstraction infrastructure, the whole aquifer can in principle be exhausted, but this would likely happen only on a seasonal basis, as subsequent rainfall in the next wet season would (partially) replenish the aquifer.

Hence, while groundwater is unlikely to run out anywhere in an absolute sense (the entire aquifer drying permanently) it is already happening in a relative sense (individual wells drying) as seen in California[30] and parts of South Asia.[31] In many cases, this is principally a reflection of the shallow nature (relative to the extensive depth of some deep aquifers) of the wells used to access groundwater but, whatever the context and cause, the situation often leads to inequitable outcomes within affected populations where those with the shallowest wells, already the poorest and most vulnerable, are the most at risk of 'running out' of groundwater.[32,33]

A common limitation in the availability of sufficient information means that our understanding of the extent and rates of depletion and timing of reaching economically infeasible pumping depths in any one aquifer will be inaccurate. These can be estimated based on knowledge of the aquifer: the dynamism and heterogeneity of individual groundwater systems, sustainable abstraction rates and volumes,[34] recharge rates, and limitations of the infrastructure used to extract groundwater. In turn, this limits our ability to predict the timing of disastrous levels of depletion from an economic point of view, let alone the timing of harmful levels of degradation of groundwater-associated ecosystems and ecosystem services.

This is true of water systems more broadly; after all, Day Zero in Cape Town's municipal water supply was first publicized about three months prior to the predicted day.[35] Furthermore, climate dynamics at various special and temporal scales and economic responses can quickly change the prevailing physical status within any one aquifer. Such climate and economic dynamics, e.g., as one aquifer gets depleted, attention/economic investment may switch by market mechanisms to another area or aquifer to compensate the unmet need for food production,[36] should be better understood.

Notwithstanding our incomplete understanding of where and when groundwater will 'run out', aquifer typologies have characteristics that lend themselves to particular patterns of depletion, as indicated in Table A8.3

Table A8.3. Nature of Aquifer Response to Depletion and Response Options

Aquifer type¥	Nature of depletion	Timeframe	Response options§
Major alluvial	Slow and incomplete If subsidence also occurs, this will permanently reduce storage, thereby limiting recovery in affected zones	Decades	Short term: Drill deeper wells – but this will make the problem worse Monitor, assess water budget, manage demand, reduce abstraction, protect and enhance recharge, change to other water sources Monitor subsidence
Complex	Depends on the aquifer	Depends on the size	Monitor, assess water budget, manage demand, reduce abstraction, protect and enhance recharge, change to other water sources

Continued

Table A8.3. Continued

Aquifer type[¥]	Nature of depletion	Timeframe	Response options[§]
Karstic	Probably some abrupt/stepwise responses due to role of individual fracture systems. Catastrophic subsidence/collapse can occur.	Depends on the size of the system or sub-systems	Monitor, assess water budget, manage demand, reduce abstraction, protect and enhance recharge, change to other water sources Prevent catastrophic subsidence through sinkholes by replacing old leaking pipes and monitor risks (e.g. land surface level declines)
Local/shallow	Locally complete, but intermittent/seasonal	Annual	Wait for next rainfall (recharge event) or wet season. Drill in neighboring aquifers. Monitor, assess water budget, manage demand, reduce abstraction, protect and enhance recharge, change to other water sources

[¥] For more details of the aquifer typology, see Chapter 1 of the report.

[§] Note, response options, and more broadly, groundwater depletion is not solely a water quantity issue. Poor groundwater quality, e.g. in upper aquifers due to pollution spurring deeper drilling and deep innate mineralised groundwater limiting the depth of useful groundwater, accelerates groundwater 'depletion'.

Notes

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23. Collective management can also be a coping mechanism in the absence of higher-level groundwater governance.

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-Ban or taxes on polluting substances
-Tradeable pollution permits, and pricing structures

28. Table indicates the relative feasibility and relevance of the various policy and management instruments in various aquifer types (+: Low, ++: Medium, ++++: High, ---: Not relevant. For more details of the aquifer typology, see World Bank. 2023. A global dataset of aquifer typologies and groundwater resources)

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Annex 7: Examining the Multi-Risk Insurance of Groundwater[1]

This appendix provides further details of results that were used to describe the potential for groundwater to act as a multi-risk insurance strategy and as well as the growing stresses of groundwater depletion.

I. Rainfall Shocks and the Impact of Groundwater on Agricultural Productivity

To study the impact of dry rainfall shocks on agricultural productivity in SSA, the analyses uses a grid cell-level data set. For the analysis, the land area is split into grid cells measuring 0.5 degree on each side, which is approximately 56 × 56 kilometers at the equator. The sample period extends from 2000 to 2013. The following equation is estimated at the global scale:

$$\Delta \ln\left(NPP_{it}\right) = \alpha_1 + \alpha_2 Z_{it}^{-1} + \boldsymbol{X}_{\boldsymbol{it}}'\lambda + f_c\left(t\right) + \theta_t + \gamma_i + \epsilon_{it}$$

Here NPP_{it} is net primary productivity in gridcell i in year t. NPP which can be measured from satellite imagery and has been used to measure agricultural performance following the past literature since it provides a common unit of productivity across different crop types (Zaveri, Russ, and Damania, 2020). NPP is linearly related to the amount of solar energy that plants absorb over a growing season and is measured in grams of carbon per square meter. NPP is combined with a land cover data set developed by the European Space Agency's Climate Change Initiative, which provides information on 37 land cover classes globally at a 300-meter grid. This ensures that plant productivity as measured by NPP is only captured in grid cells that contain significant amounts of agriculture and avoids attributing impacts to forests or other natural habitats. Rainfall variability is measured in terms of local deviations from the long-run mean using weather data comes from Willmott and Matsuura (2001). This gridded dataset contains monthly observations of precipitation and average temperature at the 0.5-degree gridcell level. We transform this data into average monthly temperature, and total precipitation (mm), per year, for each gridcell. Rainfall variability is measured in terms of local deviations from the long-run mean (annual average rainfall from 1900 to 2014). For example, a grid cell is considered to have a 1 SD dry rainfall shock if rainfall in a given year is lower than the long-run annual mean for the grid cell by at least 1 standard deviation. Control variables, including temperature and various fixed effects and time trends, are included to isolate the impact of rainfall shocks as much as possible from other factors: θ_t are year fixed effects, γ_i are grid cell fixed effects, $f_c(t)$ are country-specific time trends, $\boldsymbol{X}'_{it}$ is a vector of other control variables, including a quadratic term for mean annual temperature (°C), and log of population (in some specifications). These controls account for baseline differences in yield and other factors that vary by year. These are meant to control for changes in agricultural policies, development levels, input availability, technological levels, and time-invariant factors such as terrain slope, and soil type.

To what extent can groundwater be successful in buffering agricultural productivity from rainfall shocks? A regression of agricultural outcomes on rainfall shocks and contemporaneous groundwater usage will not yield causal estimates of the effect of groundwater irrigation on agricultural outcomes. There might be omitted variables that are correlated with both groundwater use and agricultural outcomes. In such a case, it will be difficult to know how much of the correlation between productivity and groundwater can be attributed to groundwater and how much to other factors. There are also reverse causality concerns since investments in groundwater lead to more usage of groundwater resources which in turn lead to increases in productivity that further spur groundwater investments, making causal inference difficult.

To avoid this problem, the analysis controls for whether a grid cell overlies different types of aquifers, which is an exogenous and time-invariant characteristic of groundwater availability. To understand the extent to which the relation between rainfall shocks and NPP is modulated by groundwater from local shallow aquifers in SSA, rainfall shocks are interacted with indicator variables that denote the presence or absence of local shallow aquifers in each grid using a new global dataset on aquifer typologies produced for the report (World Bank, 2023). The coefficients on the interactions show the potential for local shallow aquifer to attenuate the adverse impacts of dry shocks. Results are shown in Table 1. They suggest that even as dry shocks reduce agricultural productivity by about 6 percent in the event of dry shocks, access to local shallow aquifers can attenuate that impact by almost half the amount.

Table 1. Impact of Dry Shocks on Agricultural Productivity

Dependent variable: ΔLog(NPP)	**Sub-Saharan Africa**			
	(1)	**(2)**	**(3)**	**(4)**
Abnormal Dry Shock(0.5SD)	–0.1397***	–0.1392***		
	(0.016)	(0.018)		
x Local Shallow	0.0929***	0.0925***		
	(0.017)	(0.019)		
Dry Shock(1SD)			–0.0676***	–0.0631***
			(0.010)	(0.011)
x Local Shallow			0.0271**	0.0264*
			(0.010)	(0.010)
N	17992	16133	17992	16133

Continued

Table 1. Continued

	Sub-Saharan Africa			
Rainfall shock effects in local shallow (Linear combination of coefficients)	**–0.0468**	**–0.0467**	**–0.0404**	**–0.0367**
p-value	0.00	0.00	0.00	0.00
Cell FE	y	y	y	y
Year FE	y	y	y	y
Country Trends	y	y	y	y
Other weather controls	y	y	y	y
R-sq	0.127	0.125	0.111	0.109
Adj R-sq	0.0511	0.0488	0.0336	0.0311

Source: World Bank
Note: Dependent variable is log of NPP in cropland pixels where cropland makes up more than 35% (columns 1 and 3) or 40% (columns 2 and 4) of the share of the total land area. All regression models include grid cell fixed effects; year fixed effects; country specific trends. Other controls for contemporaneous wet precipitation shocks (i.e. whether annual precipitation in the grid cell was at least 1 SD higher than the long-run mean of the grid cell), and temperature are included. SEs are clustered at the grid level. Statistical significance is given by + p<0.1, * p<0.05, ** p<0.01, *** p<0.001.

II. Rainfall Shocks and the Impact of Groundwater on Human Capital

To study the impact of early-life shocks on child health outcomes, the analyses uses a spatially disaggregated health database of 687,652 children across 32 countries in Africa spanning over a period of 15 years using the Demographic and Health Surveys (DHS). Previous literature has documented the impacts of early life environmental shocks on child and later life health (Blom et al., 2022; Hyland and Russ, 2019; Damania et al., 2017).

The Demographic and Health Surveys (DHS) Program, sponsored by USAID, provides technical assistance for the implementation of nationally representative, stratified, two-stage cluster sample household surveys that collect data on population, health, and nutrition for over 90 developing countries around the world. We target children of 60 months or younger that have never moved since birth (the non-migrant sample) with georeferenced DHS clusters in rural areas shown in Figure 1.

The analysis focuses on anthropometric measures of children up to 5 years of age and converts childrens' heights into Z-scores using the WHO growth standards (WHO 2006). Doing so allows us to assess child height relative to well-nourished children of the same age and sex. For our main outcome variable, we use height-for-age Z-score (HAZ). Low HAZ (i.e. HAZ below –2) reflects both acute and chronic under-nutrition (stunting). We also use the composite index of anthropometric failure (CIAF) to capture the overall extent of undernutrition among children. The CIAF has been proposed (Svedberg, 2000) and used (Nandy, Irving, Gordon, Subramanian, & Davey Smith, 2005) to provide a comprehensive measure of the direction and degree of change in undernutrition over time. As the CIAF systematically captures the different combinations of anthropometric failures (i.e. including wasting and being underweight in addition to stunting) this makes it a preferred indicator of aggregated deprivation over time.

Climatic data were obtained from the African Flood and Drought Monitor (AFDM) which contains precipitation and temperature measures at a grid resolution of 0.25 decimal degrees. The AFDM, developed by Princeton University, is a hydrologic modeling platform based on available satellite remote sensing and in-situ information that is shared via a web-based user interface for operational and research use in Africa. In our analysis we define climate variability through the standard precipitation index (SPI) which measures the standard deviations of the observed precipitation from the long-term mean. We focus on climatic variability across a 12-month period and thus capture inter-year climatic variations. As in part 1, we define dry rainfall shocks based on deviations from the SPI score and use the aquifer typology dataset to measure the potential for groundwater to buffer the adverse impact of dry shocks on health outcomes.

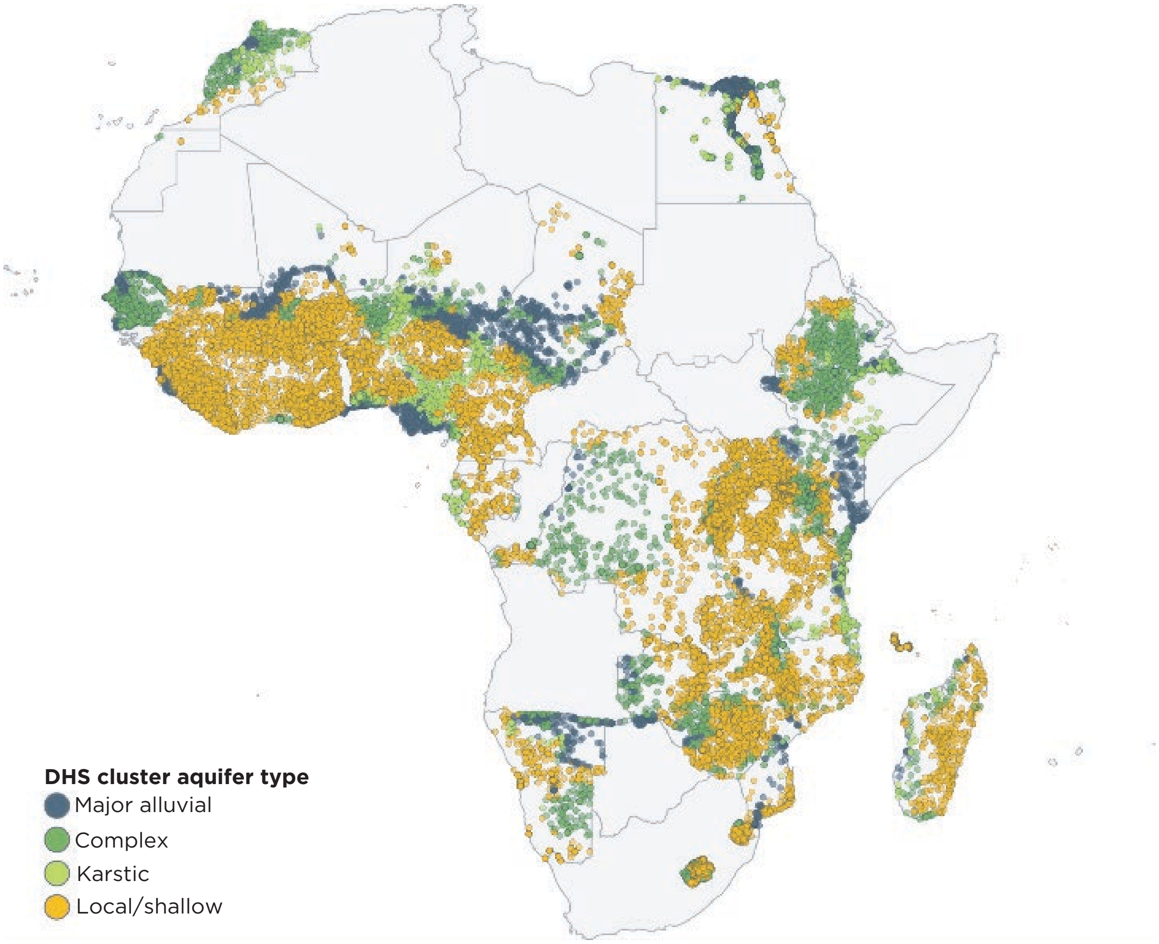
We estimate the following regression using linear regression and linear probability models:

$$Y_{it} = \beta X_{it} + \gamma Z_{it}^{-1} + \alpha W_{it} + \mu_c + \rho_{m,t} + \epsilon_{it}$$

Where X_{it} refers to a vector of largely time-invariant demographic and household characteristics like age of mother at birth, height, BMI and literacy of the mother, education of mother's partner, mother's empowerment, no. of children in the household and wealth of the household. We are particularly interested in the impacts of environmental characteristics, Z_{it}, and water-sanitation access, W_{it}, on nutritional outcomes. We calculate the fraction of exposure to dry rainfall shocks from the time of birth. $\left(Z_{it}^{-1}\right)$ and exploit quasi-random variation in the cumulative exposure to rainfall shocks experienced by different birth cohorts and compare height outcomes between exposed and non-exposed cohorts, controlling for average differences in these outcomes across birth years and across clusters. We control for time-invariant determinants of under-nutrition at the region level by controlling for cluster fixed effects, μ_c. We also control for birth-year fixed effects, $\rho_{m,t}$, to account for any unobserved time-varying factors and trends that might influence nutrition. In an alternative specification, we also control for country-month fixed effects to account for other time-varying factors that influence the growth-faltering process.

As in part I, indicator variables that denote the presence or absence of local shallow aquifers in each DHS cluster are created using a new global dataset on aquifer typologies produced for the report (World Bank, 2023). Figure 1 below shows how the DHS clusters correspond to the aquifer typology. The impact of early life shocks on child health is then assessed separately for clusters with and without access to local shallow aquifers. Table 2 presents the results. We find that exposure to rainfall shocks over the entire period from the time of birth for those children residing in clusters without access to local shallow aquifers, on average, decreases their HAZ score by 0.29 standard deviation, increases the likelihood of stunting by 0.08 percentage points and also significantly impacts the CIAF score. These effects are not significant for those clusters with access to local shallow aquifers suggesting that access to such a resource has the potential to buffer against adverse health shocks in early life.

Figure 1. **Sample of DHS Clusters and Correspondence to Aquifer Type**



Source: World Bank and Demographic and Health Survey data

III. Rainfall Shocks and the Impact of Groundwater on Economic Growth

The impacts of droughts on GDP growth follows the methodology employed in Zaveri, Damania and Engle (2023). As in part I, rainfall variability is measured in terms of local deviations from the long-run mean using weather data comes from Willmott and Matsuura (2001). Annual grid-level GDP data between 1990 and 2014 at a 0.5-degree resolution come from Kummu, Taka and Guillaume (2018a, 2018b). The data are primarily based on sub-national GDP per capita data constructed by Gennaioli, *et al.* (2013) and covers 82 countries, representing 85% of the global population and 92% of global total GDP (PPP) in 2015. Population data is taken from HYDE 3.2 (Klein, Beusen and Janssen 2010). We use World Bank Income group classifications to divide the world into low-income, middle-income (which combines lower-middle and upper-middle income countries), and high-income countries to focus on the developing sample. This is combined with aquifer typology data produced for the report and described in World Bank (2023).

As in part I, to assess the potential for groundwater to buffer the adverse global impacts on growth, rainfall shocks are interacted with aquifer types denoted by major alluvial and local shallow, two systems that are accessibly at an individual level. The interaction and linear combination term provides an indication of how much groundwater from individually accessible aquifer systems can buffer the impact of dry shocks. Results are presented in Table 3.

Each additional dry shock reduced GDP growth per capita, on average, by 0.6 percentage points but these effects are dampened in places with access to local shallow and major alluvial aquifers with the largest effects seen in major alluvial aquifers reflecting the inherent hydrogeological properties.

However, the results also urge caution in the use of groundwater. To investigate if the buffering abilities of groundwater from major alluvial aquifers are changing over time, the time period is split into three components: 1990-1998, 1998-2005 and 2005-2014. The analysis then measures the modulating effect of groundwater in the 2nd and 3rd periods relative to the 1st period conditional on a number of control variables. Results in Table 4 show that in the 2nd period, grid cells underlaid by major alluvial aquifers were able to mitigate the impact of dry shocks on aggregate growth. In years with a dry shock, these gricells experienced lower losses to economic growth over other grid cells, relative to average grid cells-level differences in dry shock sensitivity. Results also show that on entering the 3rd and last period of analysis, the buffering benefits dissipate and are no longer discernible.

To investigate the extent to which growing groundwater stress might be driving this result, we use GRACE satellite data to measure groundwater stress.

IV. The impact of Groundwater Stress

Data collected as part of the Gravity Recovery and Climate Experiment (GRACE) satellite mission was utilized to identify regions with a loss in groundwater storage. While the native spatial resolution of GRACE is ~90,000km^2 (3° x 3°), recent research utilizing machine learning algorithms has enabled downscaling GRACE-measured data to finer resolutions. In this analysis, we used downscaled GRACE-GWS data available at 0.5° resolution for Sub-Saharan Africa, the Middle East, and South Asia (Chen et al., 2023). The downscaling approach involved, first, training Random-Forest models at a 3° resolution to establish the relationship between GRACE-measured terrestrial water storage (TWS) and predictor variables such as precipitation, ET, and runoff. The trained model was then applied at the target resolution using predictor variable data at 0.5° resolution. Finally, the groundwater storage (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 groundwater storage at a 0.5° resolution for a study region that included Sub-Saharan Africa, the Middle East, and South Asia from 2003-2021. These estimates utilized GRACE-solutions from three processing centers (JPL Mascons, CSR Mascons, and GSFC Mascons) while the non-groundwater storage components were derived from two GLDAS land surface models (CLSM and NOAH). The combination of different GRACE-solution and GLDAS products resulted in 9 realizations of GWS including an ensemble mean estimates (Table 5). Details on the downscaling approach are available in Chen et al. (2023).

Table 2. Impact of Early Life Shocks on Child Health

	Baseline sample			Local/Shallow			Non Local/Shallow		
	HAZ	**Stunting**	**CIAF**	**HAZ**	**Stunting**	**CIAF**	**HAZ**	**Stunting**	**CIAF**
Fraction dry shocks	–0.2184***	0.0688***	0.0561***	–0.0949	0.0309	0.0017	–0.2970***	0.0876***	0.0910***
	–(0.045)	(0.014)	(0.015)	(0.058)	(0.019)	(0.020)	(0.073)	(0.022)	(0.024)
N	197867	197867	188313	118295	118295	112329	79503	79503	75927
Birth-Month FEs	y	y	y	y	y	y	y	y	y
Birth-Year FEs	y	y	y	y	y	y	y	y	y
Age-Month Dummies	y	y	y	y	y	y	y	y	y
Grid FE	y	y	y	y	y	y	y	y	y
Demographic controls	y	y	y	y	y	y	y	y	y
Rsq	0.187	0.135	0.128	0.192	0.134	0.121	0.175	0.134	0.139
Adj. Rsq	0.173	0.119	0.112	0.178	0.118	0.105	0.159	0.117	0.122
RMSE	1.450	0.458	0.470	1.408	0.463	0.472	1.506	0.450	0.464

Source: World Bank

Notes: Dependent variables include height for age scores (HAZ), the probability of stunting or the composite index of anthropometric failure (CIAF). Standard errors in parentheses are clustered at the grid level. Statistical significance is given by + p<0.1, * p<0.05, ** p<0.01, *** p<0.001.

Table 3. Impact of Rainfall Shocks on GDP pc Growth

Dependent variable: GDP pc growth	**Developing**	
	(1)	**(2)**
Dry shock	–0.5429***	–0.6040**
	(0.093)	(0.193)
Dry x Local/Shallow		0.0530
		(0.212)
Dry x Major Alluvial		0.1581
		(0.226)
N	667981	667955
R-sq	0.305	0.305
Rainfall shock effects (Linear combination of coefficients)		
Local/Shallow		–0.5510***
		(0.104)
Major Alluvial		–0.4459***
		(0.130)
Cell FE	y	y
Year FE	y	y
Country Trends	y	y
Wet shocks and typology interaction	y	y
Temperature control	y	Y

Notes: Dependent variable is change in gridcell log(GDP). Observations are weighted by population. All regression models include grid cell fixed effects; year fixed effects; country specific trends and temperature. Standard errors in parentheses are clustered at the Administrative 1 level. For further details on data and empirical strategy, see Zaveri, Engle and Damania (2023). Statistical significance is given by + p<0.1, * p<0.05, ** p<0.01, *** p<0.001.

Developing Indicators:

The identification of regional groundwater depletion (and deficit) hotspots is important for allocating resources and developing effective intervention strategies. In this analysis, we use two complementary indicators to identify groundwater stress hotspots across the study region (comprising of Sub-Saharan Africa, the Middle East, and South Asia). These indicators were developed taking into account differences in depletion signatures between aquifer types where - deeper aquifers with high storage (e.g. alluvial) display monotonic long-term declines, while low storage shallow aquifers exhibit shorter-term periods of deficits and recovery (Fishman et al., 2011). Overall, the indicators were used to answer the following questions -

- Negative Trend - Is there a long-term decline in groundwater storage at a given location?
- Deficit 10/20 - Has a region experienced a significant groundwater deficit period between 2010-2020?

Table 4. Impact of Rainfall Shocks on GDP pc Growth

Dependent variable: GDP pc growth	**Developing sample**	
	(1)	**(2)**
DryShock x Major Alluvial x (1998-2005)	0.9865***	0.8767**
	(0.289)	(0.268)
DryShock x Major Alluvial x (2005-2014)	0.3007	0.4597+
	(0.238)	(0.271)
DryShock(0.5SD) x Major Alluvial x (1998-2005)	–1.1532***	–0.9893***
	(0.266)	(0.242)
DryShock(0.5SD) x (2005-2014)	–0.4768*	–0.5047*
	(0.221)	(0.247)
Major Alluvial x (1998-2005)	–1.2757***	–1.6501***
	(0.334)	(0.425)
Major Alluvial x (2005-2014)	–0.1202	–0.9895**
	(0.255)	(0.378)
N	667955	667955
Cell FE	y	y
Year FE	y	y
Country Trends	n	y
Temperature control	y	y
R-sq	0.271	0.227

Notes: Dependent variable is change in gridcell log(GDP). Observations are weighted by population. All regression models include grid cell fixed effects; year fixed effects; country specific trends and temperature. Standard errors in parentheses are clustered at the Administrative 1 level. For further details on data and empirical strategy, see Zaveri, Damania and Engle (2023). Statistical significance is given by + $p<0.1$, * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Trends in Groundwater Storage

Estimating the magnitude and direction of trend is a relatively intuitive (and commonly used) metric to understand the rate of change of groundwater storage at a given location. With regards to identifying depletion hotpots, trend-based assessments aim to capture regions where long-term extraction rates exceed natural and induced recharge. As a result, these regions exhibit a long-term negative trend due to declines in aquifer storage. Studies utilizing GRACE-data have relied on trend-based assessments to identify depletion hotspots in many parts of the globe over the last few years including the Middle-East, North-Western India, Central Valley and High Plains Aquifer in USA, and the North-China Plain (Feng et al., 2013; Voss et al., 2013; Asoka et al., 2017; Rateb et al., 2020).

In this analysis, groundwater storage trends were estimated using the nonparametric Mann-Kendall (MK) trend test (Mann, 1945), while slopes were estimated using the Theil-Sen slope estimation method (Sen, 1968). The MK-trend test assesses if there is a monotonic upward or down-ward trend in a variable over time. The original MK-trend methodology was modified using the techniques developed by Yue et al. (2002) to correct for the influence of autocorrelation in the data series. We used the 'zyp' R-package (https://cran.r-project.org/web/packages/zyp/index.html) to estimate both the trend and slopes. Additionally, the trends and slopes in each grid were estimated after aggregating the monthly GRACE groundwater storage anomalies to a yearly time scale using the median GWS to minimize the effects of seasonality.

Regions were designated as depletion hotspots if they had a negative statistically significant (p-value<0.05) trend in groundwater storage. Uncertainty in depletion was calculated by estimating the number of GWS realizations (Table 5) where the trend in GWS was negative (and statistically significant; p-value<0.05). Regions were designated as having a higher probability of depletion if they had a higher number of realizations with negative trends.

Estimating Groundwater Deficits

To better identify groundwater stress across a wider range of aquifer systems, the trend assessment was complemented by an assessment of groundwater deficit patterns. The deficit-based assessment aimed to capture the extent to which groundwater storage at a given location (and time) deviates from its expected groundwater storage over the study period. Since significant deficits over extended periods of time can limit the ability of groundwater systems to help meet socio-environmental water demands, the frequency and extent of these deficit periods can be an important indicator of groundwater stress at a given location. The identification of these deficit periods is particularly important in shallow aquifer systems where periods of deficits can lead to dry and defunct wells in the system before eventual recovery (Hora et al., 2019). To conduct a deficit-based assessment, we adapted GRACE-based drought indicators (Thomas et al., 2014, 2017) where the first step of estimating groundwater deficits involves calculating the climatology (CL_i) for each month of the year by:

$$CL_i = \frac{\sum_i^k GWS}{k_i}$$

where i represents months 1, . . . , 12, k is the years of analysis from 2002-2020, and GWS is the groundwater storage anomaly for a given grid cell. The monthly climatology is then subtracted

Table 5. Breakdown of 9 GRACE-GWS realization used to estimate the range of uncertainty in GWS-trends between 2003-2020, The realization with mean GRACE-TWS and mean soil moisture storage (SMS) was used to draw major conclusions

Grace Terrestrial Water Storage (TWS)	Soil Moisture Storage (SMS)	Number of Realizations
3 TWS - JPL, CSR and GSFC	2 SMS - NOAH and CLSM	6
1 Mean GRACE TWS	NOAH	1
1 Mean GRACE TWS	CLSM	1
1 Mean GRACE TWS	1 Mean SMS	1

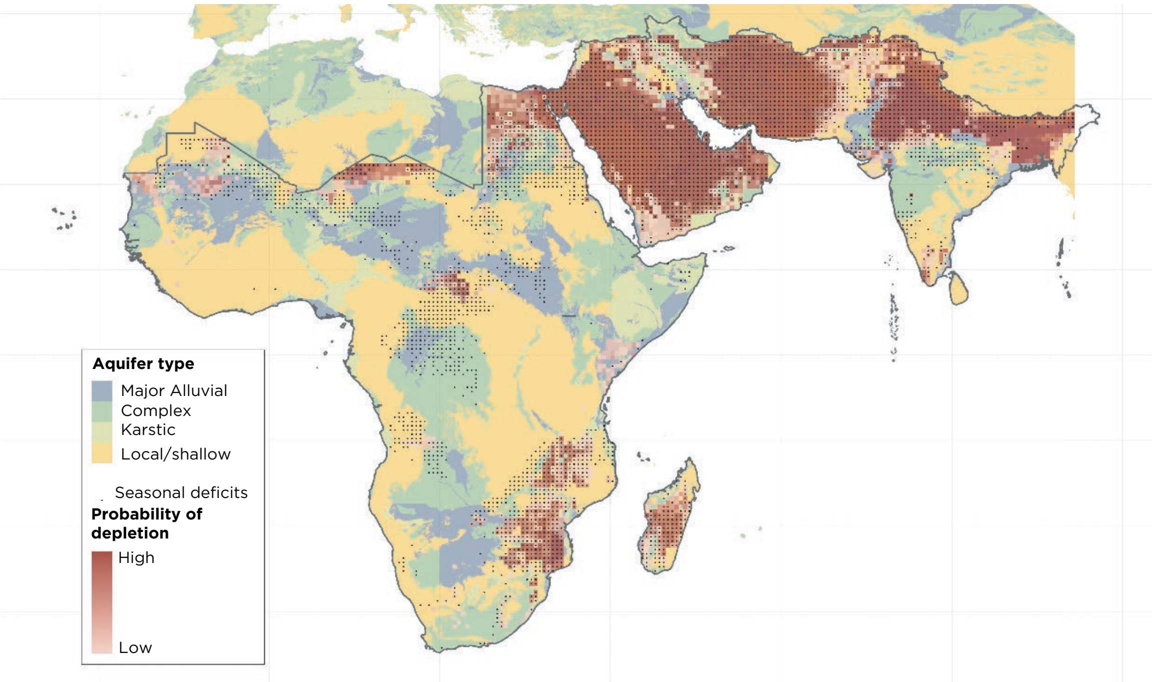
from the estimated GWS to obtain a measure of the monthly deviation from the expected monthly groundwater storage (*GSD*). This step allowed for the removal of the influence of seasonality on groundwater storage dynamics (Thomas et al., 2017). Finally, the GSD is normalized to obtain the groundwater deficit time series (*GWD*) by:

$$GWD = \frac{GSD - \overline{x_{GSD}}}{sd_{GSD}}$$

where $\overline{x_{GSD}}$ and sd_{GSD} are the mean and standard deviation of the climatogoy-subtracted residual GWS. Thus, Thus, the estimated GWD time series for each grid cell provides (in units of standard deviation) the extent to which the groundwater storage in a given month differs from its expected groundwater storage between 2003-2020.

The estimated GWD time series was then used to identify deficit periods which were assumed to be periods where the average GWD time-series value was less than –1 over any two-year window between 2003-2020 (i.e. regions where the average GWD was less than –1 standard deviations from the mean over a two-year period). Using these deficit periods, the Deficit 10/20 binary

Figure 2. Using Downscaled GRACE Data to Measure Stress



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

indicator was developed with regions being designated as a hotspot if they experienced at least one deficit period between 2010-2020.

While enabling the identification of shorter-term stress periods in aquifers that are also easier to compare across different aquifer systems (due to de-seaonalization and normalization), the deficit- based indicators also have some limitations. First, deficit periods can be triggered by both climate patterns and human extraction, and therefore, further assessments are necessary to attribute deficit periods to human interventions. Furthermore, while this analysis utilizes a -1 threshold over a two-period to designate a deficit period, there is a need for additional research to understand what thresholds better represent stress conditions in different aquifer, climate, and socio-economic systems. Figure 2 depicts both these indicators on the map.

To investigate the extent to which growing groundwater stress might be driving the dissipation in the buffering effect seen in III, we further interact the rainfall shock and Major alluvial indicator with a binary indicator for whether or not a grid cell experienced declining trends. Results in Table 6 suggest that the buffer afforded by Major Alluvial aquifers disappears in areas experiencing declining trends in groundwater storage. Instead of buffering the effect of shocks, in these areas the impact of shocks is magnified causing even further declines in growth. The implication is that there is an urgent need for policies that address the familiar collective action problems of groundwater depletion.

Table 6. Impact of Rainfall Shocks and Groundwater Stress on GDP pc Growth

Dependent variable: GDP pc growth	**Developing sample**	
	(1)	**(2)**
Dry Shock	–0.5035**	–0.2610*
	(0.193)	(0.103)
Dry x Major Alluvial	0.8715***	0.6286**
	(0.255)	(0.193)
Dry x Major Alluvial x GRACE depletion	–0.6249+	–0.6260+
	(0.333)	(0.333)
N	135162	135162
Cell FE	y	y
Year FE	y	y
Country Trends	n	y
Temperature control	y	y
R-sq	0.290	0.290

Source: World Bank

Notes: Dependent variable is change in gridcell log(GDP). Observations are weighted by population. All regression models include grid cell fixed effects; year fixed effects; country specific trends and temperature. Standard errors in parentheses are clustered at the Administrative 1 level. For further details on data and empirical strategy, see Zaveri, Damania ad Engle (2023). Statistical significance is given by + p<0.1, * p<0.05, ** p<0.01, *** p<0.001.

Note

1. This note was prepared by Esha Zaveri and Tejasvi Hora.

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