Managing Groundwater for Drought Resilience in South Asia

Delivered under the South Asia Water Initiative (SAWI) Regional Cross-Cutting Knowledge, Dialogue, and Cooperation Focus Area
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This study follows the South Asia Groundwater Forum held in Jaipur, India, in June 2016. For the forum, the World Bank and the International Water Association, through the South Asia Water Initiative (SAWI), convened 50 decision makers and 80 technical experts from across the region and beyond. Draft versions of this report and the supporting case studies were prepared for a regional (client government) stakeholder workshop to be held in Colombo, Sri Lanka, in December 2018. Regrettably, this workshop had to be canceled for reasons outside the scope of this project. The work in this report has not benefited from stakeholder review, but it will be shared with stakeholders going forward via an online launch.
Executive Summary

Background

South Asia is one of the world’s most water-scarce regions and includes some of the fastest-growing economies. Yet despite progress in agriculture and rural development over the past five decades, the region still has a large concentration of poor people who depend on climate-sensitive sectors such as agriculture, forestry, and traditional fisheries.

The region’s population of about 1.8 billion people in 2017 is expected to increase to 2.3 billion by 2050 and projections for the whole of Asia are that water demand for irrigation, industry, and households will increase by 17 to 24 percent relative to 2010. In a region already facing significant water challenges, dramatic consequences for fresh water availability are anticipated in urban and rural areas alike.

Climate, Climate Change, and Drought in South Asia

South Asia has a diverse climate and topography stretching from the glaciated mountains of the Himalayas, through arid regions of Afghanistan and Pakistan, to the tropical coasts of India, Bangladesh, and Sri Lanka. The region is drained by three major river systems—the Indus, Ganges, and Brahmaputra—which are vital to economic development and growth. Most of the region experiences three seasons: a wet season; a cool winter; and a hot, dry summer.

Already subject to high levels of seasonal and interannual variability, South Asia is vulnerable to climate change as a result of a high dependency on monsoonal rainfall and glacier-fed rivers, a high exposure to sea level rise and storm surges, and a low adaptive capacity.

Droughts are frequent in the region and have catastrophic consequences. Although the financial cost of more recent droughts is significant, the major famines that resulted from earlier droughts have largely disappeared. The capacity of rural areas and cities to respond to drought and climate change depends on water availability and management. Rainfall and temperature patterns dictate the occurrence of drought, but water management dictates the severity of the impacts.

Groundwater for Farming and Drought Resilience

Groundwater is the dominant source of water in rural South Asia and is indispensable in cities and rural areas alike. It is the backbone of irrigated agriculture across the region and is often the only source of water supply outside of areas serviced by canals.

Groundwater use has increased dramatically since the middle of the 20th century, and South Asia now accounts for about one-third of all groundwater pumped globally. Its use has been a critical factor in enabling the region to become more resilient to drought since the 1970’s. During drought, groundwater can provide emergency relief because it is able to provide water locally and more reliably than surface waters.

As the region goes through climate and socioeconomic change, the future resilience of its population and ecosystems will hinge on sustainable management of groundwater, where already a sizable proportion of the population is affected by its overexploitation. Affected areas are spread across the region, in arid and humid climates, urban and rural areas, and hard rock and alluvial aquifers. Groundwater dependence beyond replenishable limits and contamination beyond self-repair is a major challenge requiring stakeholders with insight, vision, and collaboration power to identify and implement solutions.

South Asia is expected to rely increasingly on groundwater as the region’s population and economy grow. If droughts become more common or more severe, groundwater will need to play an even more prominent role in water resources planning and management.
Groundwater Governance

Significant weaknesses exist in groundwater governance in South Asia. Legislation is inadequate, and groundwater authorities typically lack the resources and capacity to enforce even the most limited laws and compliance regimes. Ill-targeted policies such as farm subsidies for energy, and for growing high-water-use crops, have encouraged overpumping of groundwater. Poor availability of groundwater data in the region erodes the ability of water managers to carry out informed planning. Although there are positive developments in data collection and management in some areas, many countries lag in gathering data and curating existing data sets.

The consequence has been a rapid escalation of groundwater use that threatens the region’s economic gains. Overexploited groundwater systems, or those with poor water quality, undermine community resilience to drought.

Improvements to groundwater governance in South Asia and, above all, a coordinated approach across institutions are needed. Requirements are complex, but some necessary priorities include:

• Strengthening policies that reduce inequity;
• Assessing gaps in supporting laws and regulations;
• Building institutional capacity within relevant branches of government;
• Supporting the acquisition of regional and national data sets;
• Adopting a cross-sectoral approach to improving governance;
• Building regional cooperation;
• Investing in new research to protect and safely develop groundwater resources;
• Removing perverse incentives to pump excessive water; and
• Communicating groundwater issues beyond traditional stakeholders.

Management Interventions

Countries and communities across South Asia are implementing a range of techniques aimed at better management of groundwater resources. Focuses include participatory management, managed aquifer recharge, smart metering of tubewells, and conjunctive management and interventions on the energy side to discourage overpumping. Although these techniques show promise, they are adapted to specific groundwater environments and scales of intervention and require participation from local communities and government institutions—and a variety of approaches for upscaling.

To ensure groundwater can continue to support drought resilience, such management interventions must be scaled up to national-level strategies and, therefore, require the support of a strong governance framework.

Conclusion

South Asia’s achievement of many of the Sustainable Development Goals will continue to rely on groundwater. Groundwater, if well managed, can make an important contribution to climate change adaptation as aquifers provide a significant storage buffer, supporting reliable water during dry spells and drought. To ensure the continuation of these benefits, it is essential to protect aquifers, especially for the poorest members of society. Groundwater must be monitored and managed with a robust governance framework to prevent overpumping and to protect it from contamination. South Asia’s groundwater resources are critically important and already show the effects of overuse and contamination in much of the region. Improved governance, representative data collection, and better management of groundwater resources are critical prerequisites for successful climate change adaptation and resilience.
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>APFAMGS</td>
<td>Andhra Pradesh Farmer-Managed Groundwater Systems</td>
</tr>
<tr>
<td>BMDA</td>
<td>Barind Multipurpose Development Authority</td>
</tr>
<tr>
<td>BI's</td>
<td>Bhujal Jankaars</td>
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<td>DTW</td>
<td>deep tubewell</td>
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<td>EM-DAT</td>
<td>Emergency Events Database</td>
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<tr>
<td>FAO</td>
<td>Food and Agriculture Organization of the United Nations</td>
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<tr>
<td>GBM</td>
<td>Ganges-Brahmaputra-Meghna</td>
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<tr>
<td>GDP</td>
<td>gross domestic product</td>
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<tr>
<td>GRACE</td>
<td>Gravity Recovery and Climate Experiment</td>
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<td>GW</td>
<td>groundwater</td>
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<td>HLPW</td>
<td>High-Level Panel on Water</td>
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<td>IBIS</td>
<td>Indus Basin Irrigation System</td>
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<td>IGB</td>
<td>Indo-Gangetic Basin</td>
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<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<td>IWMI</td>
<td>International Water Management Institute</td>
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<tr>
<td>km²</td>
<td>cubic kilometres</td>
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<td>MAR</td>
<td>managed aquifer recharge</td>
</tr>
<tr>
<td>MARVI</td>
<td>Managing Aquifer Recharge and Sustaining Groundwater Use through Village-level Intervention</td>
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<tr>
<td>Mha</td>
<td>million hectares</td>
</tr>
<tr>
<td>MJSA</td>
<td>Mukhyamantri Jal Swavlamban Abhiyan (Chief Minister’s Water Self-Reliance Campaign)</td>
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<tr>
<td>NAQUIM</td>
<td>National Aquifer Mapping and Management Program</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration (of the United States of America)</td>
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<tr>
<td>NCT</td>
<td>National Capital Territory (of Delhi)</td>
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<td>NDVI</td>
<td>Normalized Difference Vegetation Index</td>
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<td>NGO</td>
<td>nongovernmental organization</td>
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<td>NWFP</td>
<td>North West Frontier Province</td>
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<td>PCRWR</td>
<td>Pakistan Council of Research in Water Resources</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>PGM</td>
<td>participatory groundwater management</td>
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<td>SAARC</td>
<td>South Asian Association for Regional Cooperation</td>
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<td>SAWI</td>
<td>South Asia Water Initiative</td>
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<td>SDGs</td>
<td>Sustainable Development Goals</td>
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<td>SIP</td>
<td>solar irrigation pump</td>
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<td>STW</td>
<td>shallow tubewell</td>
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<tr>
<td>SW</td>
<td>surface water</td>
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<tr>
<td>TDS</td>
<td>total dissolved solids</td>
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<td>UN</td>
<td>United Nations</td>
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<tr>
<td>UNESCO</td>
<td>United Nations Educational, Scientific and Cultural Organization</td>
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<tr>
<td>UTFI</td>
<td>underground transfer of floods for irrigation</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
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<tr>
<td>WRM</td>
<td>water resource management</td>
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<td>WWAP</td>
<td>UN World Water Assessment Program</td>
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Groundwater in a Region of Water Scarcity

The South Asia region is characterized not only by high water scarcity but also a high contrast in the availability of water. According to the AQUASTAT database of the Food and Agriculture Organization of the United Nations, the region’s average water endowment from 2013–17 was only 1,100 cubic meters per person per year, well below the corresponding statistic for Sub-Saharan Africa of 3,900 cubic meters per person per year. Bhutan was the most endowed with an impressive 101,000 cubic meters per person per year, and Maldives the least endowed with 80 cubic meters per person per year during the same five-year period. The vulnerability posed by water scarcity becomes even more apparent when one realizes that South Asia constitutes 3 percent of the world’s land mass but supports approximately 24 percent of the world’s population (World Bank 2016).

South Asia has progressed steadily in agriculture and rural development from the 1970s to the 2010s (World Bank 2017), but it still supports one of the largest concentrations of economically disadvantaged people who depend almost entirely on climate-sensitive sectors, such as agriculture, forestry, and traditional fisheries, for their livelihoods (ADB 2010; Sadoff et al. 2015; World Bank 2016). Case in point: India, which exemplifies the connection between dependency on agriculture and poverty. Agriculture supplies between 13 and 34 percent of the country’s gross domestic product, and it provides a livelihood to about half of the population. The majority of the region’s population lives in India, but the country has the highest number of people enduring water shortages, inadequate water sanitation, and the possibility of flooding. In addition, the country has the region’s highest number of undernourished children (Sadoff et al. 2015).

During coming decades, several factors will continue to influence water use: population growth and rising temperatures together with shifting trends in diet as well as consumption of products and services influenced by economic growth. The World Bank projects that between 2017 and 2050, the region’s population of 1.8 billion people will increase by 30 percent to 2.3 billion. Analysts anticipate that urban populations in the region will almost double by 2050 because of migration from rural areas spurred by climate change, and water will become even more scarce. Satoh et al. (2017) projected that, across all of Asia demand for water for irrigation, industry, and households will increase between 17 percent and 24 percent by the year 2050, relative to the year 2010. According to the same study, the number of people exposed to severe water stress could reach almost 1 billion by 2050, two-thirds of them living in Bangladesh, India, and Pakistan.

South Asia’s groundwater resources are critical to the region’s development. As of 2017 groundwater abstractions account for 40 percent of all water withdrawals in the region (Hirji, Nicol and Davis 2017), and in many places, groundwater resources are becoming overstretched (Shah 2007). This reliance most likely will increase as populations, economies, industries, and cities grow and demand greater quantities of water. Furthermore, as the effects of climate change become more pronounced—particularly short- and long-term droughts (CDKN 2014)—groundwater will need to play an even more prominent role in water resources planning and management, an expectation challenged by the unprecedented pressure on groundwater resources by rapid and extensive development across large parts of the region.

Political and economic interests may work against groundwater sustainability. In most of the region,
groundwater is free to anyone who can afford the infrastructure to extract it. Commodity pricing policies frequently favor water-intensive crops, such as rice and sugarcane. In conjunction with free or subsidized power, these policies provide a strong incentive to continue using groundwater in a matter not conducive to sustainability.

Attention at regional and global levels has focused on the role of groundwater in climate change adaptation. The High-Level Panel on Water convened by the United Nations and the World Bank recognized the importance of groundwater in achieving the Sustainable Development Goals (SDGs). In its 2018 report (HLPW 2018), the panel stressed the importance of transboundary aquifers and the environmental services provided by groundwater and recommended cooperation on transboundary aquifers; measures to prevent groundwater pollution; treatment of polluted groundwater; and management of water and wastewater to protect groundwater quality in developed areas. Other studies have presented complementary findings. Achieving many of the SDGs associated with food security, poverty, public health, renewable energy, sanitation, and water supply greatly depends on groundwater (Guppy et al. 2018).

Many studies conclude that groundwater can be an important resource for adapting to climate change (Clifton et al. 2010; GGP 2016; UNESCO-IHP 2015; WLE 2015; Kumar 2012; Shah 2009b). However, fulfilling such promise needs proper management and unyielding recognition of groundwater’s connection with surface water (Jakeman et al. 2016). As part of nature-based solutions (WWAP and UN-Water 2018), groundwater offers critical services for groundwater-dependent socioecologies (WLE 2015). Aquifers also provide significant buffer storage capacity during dry spells and drought (GRIPP 2018; WWAP and UN-Water 2018).

Recognizing the key role of groundwater in managing drought and adapting to climate change—as well as the intense pressure already placed on the resource—indicates challenges and risks associated with future water security and resilience in the region. The primary challenge revolves around the management and protection of groundwater resources and their services to sustain increasing populations faced with climatic and socioeconomic change.

Several transboundary aquifers exist within the South Asia region (Dhiman and Jain 2010). These are important internationally in terms of managing groundwater sustainably for drought resilience. Although agreements exist for the management of transboundary rivers (such as the Indus Basin Treaty), the region lacks policies for the management of internationally shared groundwater resources (Lee et al. 2018).

Awareness of the growing importance of groundwater in the region is at an all-time high, as indicated by policy reforms and documents prepared by state and national governments (for example, GOP 2018); international financing organizations (ADB 2016; World Bank 2010); UN and other intergovernmental organizations (HLPW 2018; OECD 2015; UNEP 2012; UNESCO-IHP 2015); the scientific community, (Giordano 2009; Shah 2009a); and beyond—for example, the media, civil societal groups, and others. A milestone was achieved within the region in June 2016 when the World Bank and the International Water Association, through the South Asia Water Initiative, convened 50 decision makers and 80 technical experts from across the region and around the world in Jaipur, India, for a forum dedicated to South Asia’s groundwater resources (Hirji, Mandal and Pangare 2017). The forum sought to elevate the discourse on the role that groundwater plays within multiple sectors in the region and to build a cooperative network of technical and management experts to guide sustainable groundwater use.

This study described in this document emerged from the dialogue at the Jaipur forum. It draws upon two decades of work by national and international
organizations working toward addressing groundwater governance challenges in South Asia.

**Report Objective and Approach**

This report presents the findings of a diagnostic study examining pathways and options for strengthening the governance of South Asia’s groundwater resources in the face of climate change and increasing reliance on the resource by dependent communities, particularly during times of drought. This study identifies, analyzes, and recommends management interventions that aid reforms of groundwater governance and, thus, greater sustainability of groundwater; in addition, these management interventions can strengthen drought resilience within the South Asia region.

A broad analytical framework and a series of case studies comprise most of the report. These cover a range of policy and management approaches in different hydrogeological and socioeconomic settings with reference to key groundwater challenges. They provide insights and potential solutions, tailored to specific groundwater resources and contextual problems across South Asia.

In this study, *groundwater governance* refers to the overarching framework and guiding principles for responsible collective action to ensure control, protection, and sustainable use of groundwater to benefit people and dependent ecosystems. This definition highlights the four components of governance: (a) actors and institutions; (b) legal framework; (c) information, knowledge, and science; and (d) policies and plans. *Groundwater management* refers to actions or measures undertaken by mandated actors to sustainably develop, use, and protect groundwater resources (GGP 2016). *Groundwater resilience* is the level of stress or disturbance that groundwater-dependent socioecologies can withstand without undergoing significant downturns. Stresses may be short-term because of climate variability or long-term because of climatic shifts or growing demand.

Groundwater governance studies at scales ranging from subnational through global generally use case studies to illustrate governance problems and successes (for example, Garduño et al. 2011; Kataoka 2010; World Bank 2010). Multiple analyses of case studies—such as those found in this report—are less common, but they offer a powerful tool to highlight similarities and to establish generic lessons across diverse settings (Varady et al. 2016).

**Note**

1. South Asia includes Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka.
Chapter 2
Climate, Drought, and Climate Change in South Asia

The varied topography of South Asia plays a key role in the region’s climate-related challenges. Physical features include the glaciated Himalayas in the north; the arid regions of Afghanistan and Pakistan; and the tropical coasts of Bangladesh, India, and Sri Lanka (Hirji, Nicol and Davis 2017). The region is drained by three major rivers: Brahmaputra, Ganges, and Indus (shown in map 3.2). In combination with numerous smaller river systems in peninsular India and Sri Lanka, these rivers are vital to the development and growth of the six South Asian countries through which they flow: Afghanistan, Bangladesh, Bhutan, India, Nepal, and Pakistan. The major rivers originate in the Himalayan water towers, and they are fed by both rain and snow. The Himalayan glacial ice mass—the world’s third-largest after the polar ice caps—stores precipitation in the form of snow and ice, regulating water distribution and providing continuous flows during the dry months (Lacombe, Chinnasamy, and Nicol 2018). When this snow melts or when the area experiences intense monsoon precipitation, flooding commonly occurs, but at other times, the area often has too little water, leading to intense competition between or within countries.

Climate

South Asia has three distinct seasons: wet season (June to September); winter (October to February); and summer (March to May). These seasons are controlled by seasonal rain-bearing winds (monsoons). Wet season monsoons originate in the oceans to the south and southwest and bring most of the monsoonal rains, and winter monsoons originate in the north and northeast. Despite relative uniformity in seasonal patterns, the region has great diversity in its climatic zones, which include arid and semiarid; highland; humid subtropical; and tropical dry and tropical wet (Lacombe, Chinnasamy, and Nicol 2018). Variations in precipitation illustrate this climatic diversity. Mean annual values range from less than 100 millimeters per year in the deserts of western and southern Pakistan to more than 5,000 millimeters per year in the northeastern highlands of India and in the Western Ghats mountains of peninsular India (map 2.1). The region’s long-term mean annual rainfall averages 970 millimeters per year; it ranges from 327 millimeters per year in Afghanistan to 2,666 millimeters per year in Bangladesh (Lacombe, Chinnasamy, and Nicol 2018). Monsoonal rainfall also varies temporally. Interannual variability is attributed to anomalies in the Pacific Ocean’s sea surface temperatures and other factors not clearly understood (Kumar et al. 2006). Thus, the South Asian monsoon is notoriously difficult to predict. About 60 percent of the region’s cropland relies on rainwater, so the economy of the region depends on good monsoon rainfall (Kelkar and Bhadwal 2007).

Temperature also varies considerably across the region because of altitude, latitude, and a host of other factors (Revadekar et al. 2013). The southern parts of South Asia exhibit the warmest annual average temperatures, whereas the Indo-Gangetic Plain in the north experiences the highest seasonal variations in temperature (map 2.2). The mountainous north is colder, and it receives snowfall at high altitudes.

Drought-Prone Areas

Drought is a complex phenomenon that affects society, the economy, and the environment. It corresponds to a period of unusually dry weather that persists long enough to cause water supply shortages, crop damage, and other effects.
Although not necessarily experiencing the lowest rainfall, India is the most severely drought-affected country in the region in terms of the number of afflicted people. Highly drought-prone areas cover more than 16 percent of the country and affect 11 percent of the population (SDMC 2010). The most chronically affected areas—as characterized by a 40 percent probability of rainfall deficiency of more than 25 percent of the normal rainfall—include the western parts of Rajasthan and the Kutch region in Gujarat. Other drought-prone areas in India include the remainder of Gujarat and parts of Andhra Pradesh, Bihar, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Punjab, Tamil Nadu, Telangana, Uttar Pradesh and West Bengal.

The rest of the region varies. Pakistan is highly arid, with 60 percent of its territory receiving less than 200 millimeters per year of rainfall. Across the Indus
Valley, the effect of drought on agriculture has been mitigated by the massive canal networks. Elsewhere, drought-prone areas in Pakistan include western Balochistan, Cholistan, Dera Ghazi Khan, Dera Ismail Khan, Kohistan, and Tharparkar. Certain areas experience droughts with an annual probability of as much as 30 percent (SDMC 2010). Bangladesh, though humid, experiences seasonal droughts because of its extended dry season. All areas apart from the Chittagong region experience droughts, with the Sylhet region the most affected. The Nepal Terai is also drought prone, with the far western region of the country most affected because the monsoon frequently arrives late. Droughts of short
duration regularly affect Sri Lanka; districts most affected include Ampara, Badulla, Hambantota, Kurunegala, Monaragala, Puttalam, and Ratnapura.

**Drought Effects**

Drought ranks among the most serious water management challenges of South Asia (ADB 2009; Hirji, Nicol and Davis 2017; Moench and Dixit 2004). The region’s history of drought-related calamities dates back many centuries. For example, devastating famines in India occurred in the 14th and 15th centuries because of drought that lasted multiple decades (Sinha et al. 2007). By the mid-1960s, when Green Revolution technologies had begun coming to the forefront, major famines in the region largely had become a thing of the past, according to the international disaster database (Emergency Events Database [EM-DAT]) of the Centre for Research on the Epidemiology of Disasters. This is despite the reported occurrence, since the late 1960’s, of major annual—and sometimes multyear—droughts across large swaths of the region in almost half of these years (figure 2.1).

**FIGURE 2.1. Social and Economic Effects of Drought across South Asia from 1967-2015**

Conservative estimates put the average number of affected people at 26.7 million per year and the average financial cost of these droughts at about US$113 million per year. During the five-decade period, four droughts together affected more than 100 million people as shown in figure 2.1: in 1972 (India and Nepal); 1987 (India and Sri Lanka); 2002 (India); and in 2015 (India, refer Box 2.1). These major droughts coincided with single or recurrent failure of the monsoon, and they often were associated with the El Niño phenomenon (Lacombe, Chinnasamy, and Nicol 2018). Statistics show a trend toward increasing damage costs; however, it is difficult to explain why this occurs. Determining factors likely include greater assets and increasing populations. The data set is insufficient to infer whether El Niño is occurring more frequently, and scientific understanding appears to be unclear on the complex linkages between global warming and El Niño events (Collins et al. 2010).

Available data on the regional effects of drought are limited (GFDRR 2012). The best long-term database for the region is EM-DAT, but it appears to underestimate the effects of drought because of underreporting of information. Events of the 1980s offer one indication: high population numbers were affected, yet economic damage was reported as minimal. Another indication comes from limited information for Pakistan; the country’s last recorded drought was in 1999, yet...

**Box 2.1. Socioeconomic and Environmental Effects of India’s 2015 Drought**

India’s major drought in 2015–16 caused damage estimated at US$3 billion— it was the most economically devastating drought recorded in the country. The 2015 drought directly affected about 330 million people across 10 states. Beginning in June 2015 and ending 10 months later in April 2016, the produced myriad negative effects included:

- Severe water stress across rural areas;
- Loss of rural livelihoods;
- Severe food shortages that led to a reliance on government to distribute staple grains (although deaths due to starvation were avoided);
- Acute malnutrition;
- Decline in forest health;
- Reduced capability of schools and hospitals;
- Migration to cities;
- Increased incidence of child labor, human trafficking, and child marriages; and
- Discriminatory distribution of water through water tankers to wealthier communities.

Groundwater levels across the country registered declines, and residents developed reliance on drinking water from wells within permissible water-quality limits.

Source: Sevekari 2016.
devastating drought is known to have occurred across the Balochistan and Sindh provinces from 1998 to 2002, affecting more than 3.3 million people and causing the deaths of hundreds of people from food and water shortages (Ahmad et al. 2010). Furthermore, the effects of major droughts of long duration are more easily identified than those of short duration, but short-term droughts at critical stages of the crop cycle also can have adverse effects on agricultural production and food security.

The capacity of socioecological systems to respond to drought and to climate change correlates with availability of water and management of the resource. Prevailing meteorological conditions (that is, rainfall and temperature patterns) primarily dictate the occurrence of drought; however, water resource management dictates the severity of the effects (Sayers et al. 2016). Drought-related risks and effects tend to increase with higher exposure (that is, greater populations and more assets) but tend to decrease with economic development and improved mitigation, which improve resilience. Measures to boost resilience and thus reduce effects include a host of water management interventions (canals, ponds, rainwater harvesting, tubewells, and so on).

**Climate Change**

South Asia is vulnerable to climate change because of its dependency on monsoonal rainfall and glacier-fed rivers, high exposure to storm surges and rises in sea level, and low adaptive capacity (ADB 2010; Nambi 2014). An overwhelming body of scientific evidence supports the view that climate change has commenced and will significantly affect the region even more during the coming decades and centuries (CDKN 2014; IPCC 2013). Findings from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicate the following, as summarized by CDKN (2014) and supplemented later by Lacombe, Chinnasamy, and Nicol (2018) and Mani et al. (2018):

- Temperature rises in the oceans, as a direct consequence of global warming, will increase water stored in the atmosphere, which will strengthen the intensity of the South Asian monsoon.
- Rising temperatures also will increase evaporation (water loss) and evapotranspiration rates (crop water demand); affect patterns of glacial melt, precipitation, river flows, and groundwater recharge (water supply); and increase the frequency and intensity of floods and droughts (hydrological extreme events).
- Accelerated melting of Himalayan glacial ice and snow will modify river flow regimes in the region. With limited precipitation other than the monsoon for much of the region, this meltwater represents a significant proportion of dry season flows (ranging from 41 percent of total river flow for the Indus River to 20 percent for the Ganges River basin). A shift in dominance will occur, transitioning snow- and ice-derived flows toward rainfall-derived flows.
- Retreating glaciers and warming temperatures will change future water availability substantially, in terms of both magnitude and timing (both within a year and interannually), leading to an increase in flood and drought extremes. The availability will likely differ substantially among South Asian river basins. In the short term, surface water flows will increase as melting progresses. However, over the long term, reduction in glacial flows could result in decreased dry season river flows.
- Changes in groundwater recharge processes (see chapter 3) because of climate change are difficult to deduce with any degree of confidence. The underlying processes are complex, and their interactions are not well understood (Kumar 2012).
- Rising sea levels and intense storms on the Bay of Bengal and Arabian Sea coasts will increase the risk of water quality deterioration because of salinization of coastal aquifers.
Climate change could affect many other aspects of regional life, especially because of South Asia’s dependence on agriculture and fisheries. Farm-related incomes in the region could decline by as much as 25 percent by 2050 because of diminishing crop yields associated with higher temperatures and water stress (World Bank 2016). Most South Asian countries could experience a pronounced downturn in living standards and growth of per capita gross domestic product (GDP) by 2050 (Mani et al. 2018). Possible increases in drought-related food and water shortages could cause malnutrition by the end of the century (CDKN 2014). The effects would be felt differently with respect to caste, class, ethnicity, and gender (Sugden et al. 2014). Research shows that a decline in living standards in South Asia would affect socially disadvantaged communities the most (Mani et al. 2018). More frequent, as well as more devastating, floods and droughts could launch a series of consequences, including impaired food production, loss of income security, large-scale migration within and across national borders, and increased risk of geopolitical instabilities and environmental threats (Hirji, Nicol and Davis 2017). In addition, decreased harvests of staple crops could lead to higher food prices and living costs, exacerbating rural poverty.

For South Asia—one of the world’s regions most prone to water-related disasters—the added pressure represented by climate change exacerbates the risks of unprecedented drought and other hydroclimatic extreme events (Priya et al. 2017). The threat level is at least sufficient to reinforce the need to prioritize mitigation and preparedness in water resources planning and management.

Note
1. The Terai region covers the southern slopes of the Himalayas in India and Nepal. It originally was composed of alluvial grassland and forest ecosystems. The land use is now more patchy; it also includes agricultural fields and urban settlements (Semwal 2005).
Chapter 3
Overview of Groundwater in South Asia

Regional Hydrogeology

An assessment of regional hydrogeology (Mukherjee et al. 2015) identifies seven aquifer types: (a) Indo-Gangetic basin (IGB) alluvial aquifers (alluvial), (b) Indian cratonic aquifers (hard rock), (c) Himalayan crystalline aquifers (hard rock), (d) North West Frontier plain aquifers, (e) other unconsolidated aquifers, (f) other semiconsolidated aquifers, and (g) other crystalline aquifers (map 3.1).

The IGB is among the world’s most important aquifer systems with regard to groundwater availability and yield capacity. Significant groundwater potential exists in vast deposits of Quaternary Period sediments by the major Himalayan rivers of the Indian subcontinent—the Brahmaputra, Ganges, and Indus. These extend over most of Bangladesh; eastern, northern, and northwestern India; and eastern Pakistan (map 3.1). The thickness of these unconsolidated aquifers (of fluvial or alluvial origin) often exceeds 300 meters. Although often mapped as a single unit, these aquifers comprise a heterogeneous, connected system with lateral and vertical spatial differences in groundwater recharge, permeability, storage, and water chemistry (MacDonald et al. 2015). Within the Pakistan part of the Indus basin about 10 million of the 16 million hectares of surface area overlie fresh groundwater, and according to Qureshi (2015), the remainder is saline (that is, more than 2,500 milligrams per liter of total dissolved solids). The Ganges-Brahmaputra-Meghna (GBM) river system discharges to the Bay of Bengal, and it has formed the largest deltaic system of the world, covering all of Bangladesh as well as the southern and eastern parts of West Bengal in India. According to Dhiman and Jain (2010), the IGB aquifer system crosses international borders, forming important transboundary aquifers shared in South Asia by India and Pakistan (Indus basin aquifer); India and Bangladesh (Ganges and Brahmaputra basin aquifers); India and Nepal (aquifers of Ganges tributaries); and Bhutan and India (aquifers of Brahmaputra tributaries).

Beyond the IGB, unconsolidated aquifers lie within relatively narrow belts of moderate thickness (less than 100 meters in general) along some of the prominent river basins of peninsular India that discharge to the Arabian Sea (for example, Narmada River) or the Bay of Bengal (for example, Cauvery, Godavari, Krishna, and Mahanadi rivers). Such aquifers also lie in Balochistan Valley and other intermontane valleys in the North West Frontier Province of Pakistan and parts of Sri Lanka.

Most of peninsular India is underlain by low-storage fractured rock aquifers largely composed of crystalline rocks, consolidated sedimentary formations, and multilayered basalt flows. Crystalline formations also extend across Sri Lanka and western Pakistan. These hard rock aquifers generally have low to moderate potential. Although far less productive than alluvial aquifers, they are extremely important for food and water security in these regions. However, developing water sources from hard rock aquifers is intrinsically difficult because of aquifer heterogeneity. Striking productive zones within the aquifer is not guaranteed, particularly because rural communities lack the means to access scientific surveying tools; thus, negative results can impair livelihoods severely (Garduño et al. 2011). Many hydrogeological assessments at subregional or more local scales provide detailed information on aquifer characteristics, groundwater flow systems, water balance, and water quality (for example, CGWB 2012; MacDonald et al. 2015; Panabokke and Perera 2005; Saha et al. 2016).

Except in irrigation areas, monsoon rainfall primarily recharges aquifers in the region (Mukherjee et al. 2015). The 2017 national assessment of groundwater in India
shows that 58 percent of replenishable groundwater resources comes from precipitation during the monsoon season. This figure increases to 67 percent when the assessment includes rainfall-derived recharge from the remainder of the year (CGWB 2017). In areas with highly developed canal networks (such as large irrigation schemes in the IGB), seepage from irrigation canals and return flows from irrigated fields contribute the most to recharge, particularly in arid regions (MacDonald et al. 2015; Qureshi 2015) and are recognized as contributing the major proportion of groundwater recharge in the Upper Indus basin (A.D. Khan et al. 2016).

Natural groundwater recharge rates across the region vary by more than two orders of magnitude.
(Mukherjee et al. 2015), reflecting substantial differences in geological conditions and climatic zones, the latter ranging from tropical to arid and from humid to highland. Recharge values vary from less than 2 millimeters per year in highly arid parts of the middle Indus basin to more than 300 millimeters per year in the GBM delta (map 3.2).

Role and Significance of Groundwater Resources in the Region

Groundwater is the dominant source of rural water. It is indispensable to cities and towns, which struggle to cope with the rapid pace of urbanization using surface water alone. Furthermore, groundwater serves as the backbone of irrigated agriculture across the region;
it is often the only source of water outside canal command areas. Since the middle of the twentieth century, groundwater use has increased dramatically across much of South Asia, placing the region’s consumption among the highest in the world, as indicated in figure 3.1 (de Chaisemartin et al. 2017; Shah et al. 2007; Shamsudduha 2013; van der Gun 2012). In some areas, this increase in groundwater use is enabled by unmanaged recharge through leakage from irrigation canals and command areas (Evans et al. 2012; MacDonald et al. 2015) and by managed aquifer recharge (Dillon et al. 2019).

Groundwater abstraction in the region constitutes about one-third of all groundwater pumped globally (Hirji, Mandal and Pangare 2017). Three South Asian countries account for almost half of the groundwater abstracted globally for irrigation: Bangladesh at 29 cubic kilometers per year; India at 251 cubic kilometers per year; and Pakistan at 62 cubic kilometers per year (table 3.1). Regional estimates indicate that about 30 million private dug wells and tubewells abstract about 354 cubic kilometers of groundwater each year (table 3.1). This dependency becomes even more apparent when one considers that groundwater accounts for only 15 percent of renewable water resources in the region but about 34 percent of water use. Of the estimated 561 cubic kilometers per year of renewable groundwater, about 63 percent has been developed (table 3.1).

Figures in table 3.1 are estimates because there are few measurements in the South Asia region of surface water seepage or irrigation return flow on the recharge side, and no measurement of use (as highlighted by discrepancies among figures in the literature). The table shows that groundwater use, as a proportion of recharge, in individual countries varies enormously, from 0 percent for Bhutan to over 100 percent for Bangladesh.

During the past two centuries, South Asia’s irrigation sources have shifted from a dominance by surface water drawn largely from public canals and ponds to a dominance by groundwater (figure 3.2). Groundwater wells have been meeting agricultural water demands for centuries in South Asia (Shah 2009a). At the beginning of the nineteenth century, about 2 million hectares of land were irrigated by groundwater.

**FIGURE 3.1. Expansion in Groundwater Use in Some South Asian Countries**

![Graph showing expansion in groundwater use in South Asian countries from 1940 to 2010](source: Adapted from Shah 2007. Note: Reliable data for other South Asian countries are not available.)
Figure 3.2 makes it clear that though groundwater has long played an important role in irrigated agriculture in South Asia, its relative share has increased enormously since the 1970s with improved access to, and reduced costs of, drilling and pumping technologies as well as rising water tables in major irrigation areas. In India alone, Minor Irrigation Census data show that the total area irrigated by groundwater increased from 6 million hectares in 1950–51 to 11.9 million hectares in 1970–71, then to 33.8 million hectares in 2000–01, and to 63.4 million hectares in 2014–15. During the seven-year period between the 2006-7 and that in 2013-14, the number of dug wells in use declined by about 4.5 percent from 0.92 to 0.88 million and the number of deep tubewells increased by 80 percent from 1.44 to 2.61 million (GOI 2017).

TABLE 3.1. Estimated Renewable Groundwater Recharge and Use in South Asian Countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Average annual groundwater recharge (km³/yr)</th>
<th>Groundwater use (km³/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afghanistan</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>21</td>
<td>29</td>
</tr>
<tr>
<td>Bhutan</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Indiaa</td>
<td>432</td>
<td>251</td>
</tr>
<tr>
<td>Nepalb</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>Pakistanc</td>
<td>61 (13 rainfall + 48 leakage)</td>
<td>62</td>
</tr>
<tr>
<td>Sri Lanka¢</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>561</td>
<td>354</td>
</tr>
</tbody>
</table>


Note: The AQUASTAT model determines recharge based on precipitation, although this can lead to significant discrepancies (see note c). km³/yr = cubic kilometers per year.

a. These national figures mask the reality that about 30 percent of administrative blocks in India are experiencing groundwater depletion (see Review of Regional Groundwater Challenges section).

b. Groundwater values cover only the Terai region; hence, this volume is an underestimate because spring flows are an important water source in mountainous areas.

c. Figures come from Young et al. 2019. Pakistan’s groundwater balance is dominated by the Indus basin, in which the major portion of recharge is leakage from the irrigation system, thereby leading to a double counting error (where the same volume of water is counted as inflow to surface water and as recharge to groundwater).

d. These figures account for groundwater abstracted for town water supplies only (reflecting available data).
Development of groundwater resources has enhanced agricultural productivity, which in turn has improved food security and lowered rural poverty (Giordano and Villholth 2007; Jacoby 2017). In most of the region, groundwater bridges the gap between water demands of crops and water available via precipitation. Demographics of groundwater irrigation reveal extremes, ranging from subsistence for smallholder and marginal farmers to the creation of wealth for farmers with large landholdings.

Agriculture’s use of groundwater underpins the livelihood of 54 to 61 percent of the South Asian population (Villholth and Sharma 2006). Groundwater supports smallholder irrigated agriculture in much of Bangladesh, India, Nepal Terai, Pakistan (particularly in Punjab and Sindh provinces), and northern Sri Lanka (map 3.3). In canal areas, groundwater is a supplementary source (particularly in drier months), but outside canal areas, it is largely a primary source. In more specific terms:

- About 60 percent of India’s irrigated area is serviced by groundwater (Shah 2009a);
- Almost 80 percent of Bangladesh’s cultivated area is irrigated with groundwater (Qureshi, Ahmed, and Krupnik 2014);
- More than 60 percent of irrigation water in Pakistan comes from groundwater (largely originating from surface water). The number of tubewells mushroomed from 88,000 in 1970 to more than 1 million by 2016 (A.D. Khan et al. 2016); and
- An estimated 50,000 lined and unlined agrowells1 in the Dry Zone of Sri Lanka support high-value crops (Pathmarajah 2007).

Many factors underpin the boom in groundwater infrastructure. These include a lower general cost and higher source quality. Groundwater offers greater reliability and higher control for users than surface water (see Giordano and Villholth 2007; Shah 2009a; van der Gun 2012). Dug wells and tubewells have become the sources of choice for households, farmers, industries, and water service providers because of the largely ubiquitous presence and accessibility of aquifers. Groundwater’s attraction has increased as technologies for drilling and pumping have become more affordable to rural communities and because of government energy subsidies for pumping. Across the arid and semiarid parts of the region—notably, in northwest India, the rain shadow belt of western peninsular India, and most of Pakistan—it is often the dominant or even the sole source of water. Farmers increasingly opt for groundwater, which provides water on demand and typically increases productivity in irrigated areas. Greater productivity leads to more income from fields irrigated with groundwater versus fields irrigated by surface water (Hirji, Mandal and Pangare 2017).

Review of Regional Groundwater Challenges

Three groundwater-related regional challenges threaten the livelihoods of millions of people in South Asia. They are widespread overexploitation of groundwater, the water insecurity of major cities and extensive contamination of the resource.

Groundwater Overexploitation

Groundwater resources—and the ecosystems and human settlements that depend on them—face increasing stress because of half a century of resource development to satisfy increasing demands by expanding populations and socioeconomic development. Information about the overexploitation of groundwater in South Asia has become well known, thanks to various publications (for example, Garduño et al. 2011; Rodell, Velicogna, and Famiglietti 2009; Shah 2009a; World Bank 2010). Groundwater overexploitation (also referred to as depletion here) on a massive scale has emerged in such areas as northwestern Bangladesh; northwestern and peninsular India; and parts of the Indus Valley Plain.

In the absence of assessments based on field data, global hydrological modeling indicates areas of

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exploitation, as shown in map 3.4. Areas affected extend over both hard rock and unconsolidated aquifers. As expected, groundwater depletion is prevalent in arid and semiarid areas because of limitations in groundwater recharge combined with high demands for irrigation. Depletion is also apparent—and spreading—across more humid areas, such as parts of Bangladesh and in Uttar Pradesh, West Bengal, and other parts of India. In broad terms, patterns of depletion correlate with intensity of groundwater infrastructure and intensity of groundwater irrigation (compare map 3.4 to map 3.3). Other influences on
pumping behavior of farmers include energy policies and such factors as crop type, which determines water demand (Shah et al. 2009, Shah et al. 2018).

Regional models do not adequately indicate depletion of aquifers in the fresh groundwater areas of Punjab, as shown in map 3.4, as records show declines in groundwater levels across many parts of the Indus basin in Pakistan (Qureshi et al. 2010). The Indus basin in Pakistan not only has growing groundwater depletion but also widespread areas of shallow water tables and saline groundwater, leading to problems associated with waterlogging and secondary salinization (A.D. Khan et al. 2016; Qureshi 2015; van Steenbergen, Basharat and Lashari 2015). Shaded areas of map 3.5

Source: Döll et al. 2014.
show water table trends (rates of rise or decline) across the IGB in Bangladesh, India, and Pakistan, as well as areas of increasing depletion (such as in the Punjab of India and Pakistan). The areas showing rises in water table (such as in the Sindh Province in Pakistan) are associated with waterlogging and salinization.

Before development of canals in the Indus basin irrigation system (IBIS) a century ago, groundwater was often saline and too deep to access (Qureshi et al. 2010). By 1960, groundwater levels had risen 20 meters or more because of seepage from from canals and overirrigation. Large-scale use of groundwater commenced in the 1960s with thousands of tubewells to address salinity and waterlogging issues. Most groundwater use in IBIS occurs conjunctively with the use of surface water (van Steenbergen, Basharat and Lashari 2015). Nowadays, groundwater helps farmers cope with unreliable surface water supplies to achieve higher crop yields, and farmers use it together with surface water when groundwater is too saline to use directly (Qureshi 2015). In Pakistan’s Balochistan, groundwater levels are declining at a rate of 2 to 3 meters per year, and in upland areas outside major command areas, groundwater levels declined by as much as 5 meters per year (van Steenbergen, Kaiserani, Khan and Gohar 2015).

According to estimates of Indian groundwater resources (based on 2013 data), about 30 percent of administrative units were designated as having overexploited (nonsafe) levels of development, and an additional 1 percent of them have saline groundwater (CGWB 2017). In India, the estimated area affected by overexploitation in 2013 covered about 50 million hectares squared. In more severely affected areas of India, such as the New Capital Territory (NCT) of Delhi and parts of Haryana and Rajasthan, estimates indicate that groundwater abstraction could exceed recharge by 25 to 40 percent (Saha et al. 2016). Scaling out from the Central Groundwater Board’s figures (2017) based on the model by Döll et al. (2014) suggests that groundwater depletion across South Asia affects about 60 million hectares of land.

Groundwater depletion is not a major concern in Nepal Terai, where only 20 percent of available dynamic groundwater recharge is used, up from just 10 percent in 1996 (Saha et al. 2016). A high-contrast situation has emerged in the rapidly urbanizing and physically constrained intermontane valley aquifers of Kathmandu in central Nepal; estimates indicate that total abstraction from the valley exceeds recharge by more than two. Between 1980 and 2008, groundwater levels
declined by more than 30 meters in some locations with associated losses in well yields (Pandey et al. 2010). A similar situation is reported in the intermontane valley aquifer of the Kabul River basin, which supports domestic water supply in the urban area of Kabul in Afghanistan (Uhl 2006).

Analysis of groundwater trends over 20 years in Bangladesh reveals that groundwater levels are declining (more than 1 meter per year) in urban and peri-urban areas around Dhaka as well as in north central, northwestern, and southwestern parts of the country (0.1 to 0.5 meters per year), where intensive abstraction of groundwater occurs to cultivate dry season rice (Shamsudduha et al. 2009). Some normalization of levels takes place in areas that are hydraulically well connected to large rivers. Elevations in sea levels have led to rising groundwater levels (0.5 to 2.5 centimeters per year) as observed in the estuarine and southern coastal regions. Shamsudduha et al. (2009) revealed the unsustainability and imbalance associated with groundwater irrigation. Hotspot areas include more elevated parts of the Barind Tract in the northwest as well as in coastal areas, which are increasingly susceptible to seawater intrusion.

MacDonald et al. (2016) estimated groundwater storage changes across the IGB alluvial aquifer from in-place in situ field measurements (2000–12). The researchers calculated a net average depletion rate of 8 cubic kilometers per year (ranging from 4.7 to 11 cubic kilometers per year), with significant variability across the basin. Using 2002–08 satellite data from the Gravity Recovery and Climate Experiment (GRACE) at a 400 × 400 kilometer resolution, Rodell, Velicogna, and Famiglietti (2009) estimated that groundwater storage had declined by 17.7±4.5 cubic kilometers per year over the hotspot extending across four Indian states and territories (Haryana, NCT Delhi, Punjab, and Rajasthan). Different resolutions explain the discrepancy. Although GRACE analyses provide important insights into regional groundwater trends, they have coarse spatial resolution and have greater accuracy when constrained by adequate in situ observations.

Groundwater underpins a variety of ecosystem services upon which South Asian societies depend—agricultural systems, riverine floodplains, springs, terrestrial forests, wetlands, and others. When groundwater is abstracted for irrigation or other purposes, other parts of the system will be affected to some degree (WLE 2015). Increasing groundwater development and declining groundwater storage have severely degraded the ecosystem services upon which agrarian and urban societies depend. In the Indian Himalayan region, for example, half of the 3 million springs that provide water for tens of millions of people have dried up or become seasonal; in addition, concerns have arisen about water quality (NITI Aayog 2018).

Rapidly declining groundwater levels result in a variety of negative effects—diminished river flows during dry seasons; drying out of wetlands and springs; impaired rural and urban water supplies; land subsidence; loss of crops and livestock; reduced well yields and pump failure; salt water intrusion in coastal areas; and upconing of saline water in inland areas (Shah 2009a). Most knowledge comes from local sources or anecdotes; researchers lack a comprehensive assessment of the effects of groundwater overexploitation on ecosystems in the region.

Excessive lowering of groundwater levels causes wells to dry out and makes pumping more expensive, which disproportionately affects the least affluent members of society. As overexploitation exerts its effects, farmers have little choice but to drill deeper, which only worsens the situation. Depletion of aquifers in rural areas may exacerbate outmigration to cities for employment (Fishman, Jain, and Kishore 2013). Inequity in water access continues to be a serious issue, especially with regard to increased water scarcity. Small and marginal farmers are often at a disadvantage; they cannot compete with large farmers in well deepening or using water-saving irrigation technologies. Thus, small and marginal farmers pay a high price as the first victims of groundwater depletion (Reddy 2005). Farmers are striving to exit their
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groundwater irrigation-based livelihoods and are encouraging the next generation to develop income sources that depend less on water. Nevertheless, depletion of groundwater can undermine social sustainability and may affect food security on a local level—and increasingly at larger scales.

Water Insecurity of Groundwater-Dependent Cities and Towns

Water supplies for major cities and towns depend on groundwater to fill gaps in demand not met by other sources. Across the highly productive IGB aquifer, groundwater is often the major source of municipal supplies (CGWB 2011; Foster et al. 2010; Hasan, Burgess, and Dottridge 1999; Pandey et al. 2010). Many rapidly expanding cities in the region—including several megacities with more than 10 million people—greatly depend on groundwater. For example, Dhaka abstracts 0.76 cubic kilometers per year, or 87 percent, of its municipal water supply from public wells because treatment costs are lower than they are for surface water (Uddin and Baten 2011). Private wells supplement public wells to supply water for industry and domestic purposes.

In net terms, the quantities of water withdrawn for municipal supplies are modest in comparison to agriculture (7 percent compared with 91 percent, according to the AQUASTAT database). Because 34 percent of South Asia’s population (in 2018) resides in cities, and this figure is anticipated to increase to 51 percent by 2050, greater consideration should be given to urban groundwater issues. Groundwater abstraction in urban areas is highly concentrated, leading to local declines in groundwater levels and raising concerns about the long-term security of supplies (Foster et al. 2010). Such cities as Aurangabad, Bhuj, Delhi, Dhaka, Kathmandu, Lahore, and Lucknow (among many others) are facing both falling groundwater levels and contamination (table 3.2).

Because of inadequate infrastructure and resources, cities and industrial areas do not appropriately collect, treat, and dispose of their solid and liquid wastes. This results in groundwater contamination of surficial aquifers. Groundwater levels have fallen by tens of meters in some cities, which leads to land subsidence in some geological settings (Ganguli 2011). Gradual sinking of land surface can be quite costly as a result of damaged urban infrastructure, increased risk of inundation related to sea-level rises in coastal settlements, and deterioration of groundwater quality by intruding sea water. Excessive groundwater pumping can also increase levels of contaminants, such as arsenic (Erban et al. 2013; Radloff et al. 2011; Smith, Knight, and Fendorf 2018; Winkel et al. 2011).

Most regional cities face severe scarcity of water, sometimes manifesting itself in water crises, particularly in the larger economies of Bangladesh, India, and Pakistan. These crises primarily occur in the summer months leading up to the monsoon. The problem of water scarcity is compounded by population growth and high rates of migration from rural areas to cities. Urban growth targets peri-urban areas, where lower-value agricultural land is subsumed to a host of higher-value urban land uses that demand water and generate solid and liquid wastes (Howard 2012). Land use changes can affect both the quantity and quality of groundwater. Urban expansion is associated with the blanketing of fields and water courses with impervious materials (primarily concrete), which diminishes local recharge areas. For example, the 500 most populated cities of India added 2,275 square kilometers of impervious surface area between 2000 and 2010 (Wang et al. 2017).

Declining groundwater levels in or near urban areas may be attributed to multiple factors: reduced recharge; higher population densities; enhanced groundwater pumping; and diversion of surface water in groundwater recharge zones. Typically, limited water resources planning takes place, and water supply provisions are basic. Private operators usually step in to supply this market. Under this scenario, urban-rural tensions can develop, and disputes or conflicts typically arise because of quantity (between sectors
### TABLE 3.2. Examples of Key Issues in Some Groundwater-Dependent Cities

<table>
<thead>
<tr>
<th>City</th>
<th>Population (million)</th>
<th>Rainfall (mm/yr)</th>
<th>Aquifer type</th>
<th>Groundwater dependency</th>
<th>Groundwater abstraction (km³/yr)</th>
<th>Key issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dhaka, Bangladesh</td>
<td>19.6</td>
<td>2,100</td>
<td>Alluvial</td>
<td>High</td>
<td>0.76</td>
<td>Major pollution of shallow aquifers; arsenic mobilization to deeper aquifers; high rates of groundwater depletion; land subsidence</td>
</tr>
<tr>
<td>Aurangabad, India</td>
<td>1.2</td>
<td>710</td>
<td>Hard rock (basalt)</td>
<td>Medium</td>
<td>—</td>
<td>Potential contamination from poor sewage system; seasonal groundwater depletion; limited tanker supplies in summer</td>
</tr>
<tr>
<td>Bhuj, India</td>
<td>0.25</td>
<td>370</td>
<td>Semiconsolidated</td>
<td>Medium</td>
<td>0.002-0.003</td>
<td>Declining groundwater levels and increasing salinity because of upconing of saline groundwater from lower levels.</td>
</tr>
<tr>
<td>Delhi, India</td>
<td>28.5</td>
<td>612</td>
<td>Alluvial</td>
<td>Medium</td>
<td>0.48</td>
<td>Groundwater depletion; water quality deterioration in terms of fluoride, nitrate, salinity, nitrates, and some heavy metals (especially around landfills, industrial areas, and major drains).</td>
</tr>
<tr>
<td>Lucknow, India</td>
<td>3.5</td>
<td>1,140</td>
<td>Alluvial</td>
<td>Medium</td>
<td>—</td>
<td>Elevated iron, manganese, and nitrate; organic carbon in the first productive aquifer because of wastewater seepage; groundwater depletion</td>
</tr>
<tr>
<td>Kathmandu, Nepal</td>
<td>1.3</td>
<td>1,400</td>
<td>Alluvial (intermontane valley)</td>
<td>Medium</td>
<td>—</td>
<td>Groundwater quality deterioration of shallow aquifers because of anthropogenic activities (ammonia, arsenic, BOD, elevated bacterial indicators, iron, manganese, methane, nitrate); high rates of groundwater depletion.</td>
</tr>
<tr>
<td>Lahore, Pakistan</td>
<td>11.7</td>
<td>607</td>
<td>Alluvial</td>
<td>High</td>
<td>2.0</td>
<td>Contamination from wastewater; groundwater depletion; land subsidence; reduced local recharge (because of reduced inflows and local increase in impervious areas); saline intrusion.</td>
</tr>
</tbody>
</table>


Note: BOD = Biological Oxygen Demand; km³/yr = cubic kilometers per year; mm/yr = millimeters per year; — = not available.

a. For more information on population statistics, see http://worldpopulationreview.com/.
b. High dependency implies that groundwater is a major source of water; medium dependency implies that public groundwater wells supplement surface water supplies.
Groundwater Contamination

Across parts of the region, groundwater quality is compromised by contaminants naturally present in the aquifer (geogenic contaminants) as well as by those that seep into groundwater because of industrial waste disposal, intensive agrochemical use, poor sanitation in villages or developed areas, and wastewater discharge. In broad terms, the most widespread rural problems reportedly have geogenic origins; however, in towns and cities, anthropogenic contamination is more problematic (CGWB 2011; Mukherjee et al. 2015). In areas where irrigation water is the principal source of recharge, irrigation will increasingly affect groundwater quality. Irrigation water has significantly higher salt content than rain water (Foster et al. 2018), and groundwater quality may suffer because of agrochemicals, particularly nitrogen, and the complex geochemical reactions arising from a system out of equilibrium. These same geochemical reactions affect long-term soil chemistry and structure. Table 3.3 lists the main groundwater contaminants in the region and their likely effects. A more detailed indication of health effects of individual groundwater contaminants is reported by the World Health Organization (WHO), 2006.

The most significant contaminants in groundwater of geogenic origin are dissolved arsenic, fluoride, and salinity (derived from mineral or marine sources or from evaporative concentration) (map 3.6). Studies have emerged showing that groundwater in several parts of India is contaminated by uranium at levels in excess of the WHO drinking water standards of 30 micrograms per liter (Coyte et al. 2018). Although the primary source of this contamination is geogenic, anthropogenic factors assist mobilization of contaminants and exacerbate the problem. These factors include the decline of groundwater levels and the presence of contaminants, such as nitrate (Coyte et al. 2018; Farooqi et al. 2007). Arsenic contamination across the

<table>
<thead>
<tr>
<th>Groundwater quality issue</th>
<th>Affected regions</th>
<th>Potential sources</th>
<th>Likely effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>Central and southern Bangladesh; eastern Gangetic Plain; lower Indus Plain</td>
<td>Geogenic origins; aggravation by complex processes of geogenic or anthropogenic origin</td>
<td>Arsenosis; skin lesions; possibility of lung and/or bladder cancers</td>
</tr>
<tr>
<td>Fluoride</td>
<td>Western and peninsular India; Lower Indus basin; western Pakistan</td>
<td>Geogenic; aggravation by groundwater overdevelopment</td>
<td>Fluorosis: brittle teeth and bones and adverse skeletal effects</td>
</tr>
<tr>
<td>Uranium</td>
<td>Several states in India</td>
<td>Geogenic</td>
<td>Deterioration of kidney function</td>
</tr>
<tr>
<td>Salinity</td>
<td>Coastal aquifers across the region; irrigation areas; lower and middle Indus plains</td>
<td>Anthropogenic (due to over pumping); geogenic</td>
<td>Crop loss; kidney stones</td>
</tr>
<tr>
<td>Microbiological</td>
<td>All over South Asia</td>
<td>Urban areas: improper management of sewage effluent; rural areas: poor isolation of latrine pits or water wells, open defecation</td>
<td>Diarrheal disease, especially in children; stunting</td>
</tr>
<tr>
<td>Agrochemicals</td>
<td>Middle Indus and upper Ganges; most agricultural areas</td>
<td>Chemical use in agriculture (fertilizer, pesticides, and so on)</td>
<td>Effects dependent on contaminant (nitrate can be toxic to infants)</td>
</tr>
<tr>
<td>Industrial effluents</td>
<td>Industrial areas all over South Asia</td>
<td>Improper discharge of untreated industrial effluents</td>
<td>Effects dependent on contaminant</td>
</tr>
</tbody>
</table>

Source: Krishnan 2009.
Arsenic poisoning is a serious human health issue in these densely populated, groundwater-dependent regions. In Bangladesh, data from more than 50,000 water samples show that arsenic is present at levels higher than 10 micrograms per liter in 60 of the country’s 64 districts and at levels higher than 50 micrograms per liter in 50 districts (Das et al. 2009). Arsenic contamination also pervades the shallow aquifers of the Indus Valley (Podgorski et al. 2017). In India, the shallow aquifer system in the geologically more recent alluvial belt, and the deltaic plains of the Ganges and Brahmaputra rivers, endure the most contamination, affecting the states of Assam, Bihar, Uttar Pradesh, and West Bengal. Elevated levels of geogenic arsenic have also been reported in hard rock aquifers but to a lesser extent than alluvial aquifers (map 3.5). Assessments reveal arsenic contamination (more than
Fluoride levels above the WHO guideline of 1.5 milligrams per liter have been reported in parts of India, Pakistan, and Sri Lanka. In India, fluoride contamination is more prevalent than arsenic, and it has been reported in 276 districts in 20 states. However, fluoride contamination is more prevalent in the hard rock and marginal alluvium areas in southern, central, and eastern states, in addition to widespread occurrence in aeolian deposits in the states of Rajasthan and Gujarat. In Pakistan, fluoride-contaminated groundwater is reported in Balochistan, Punjab, and Sindh. Excessive fluoride levels, along with iron and chloride, have been reported in Sri Lanka (Lawrence et al. 1988).

Salinity in groundwater affects its suitability for drinking and agricultural use. Large tracts of western and northwestern India and the lower Indus basin in Pakistan are affected by high groundwater salinity. Inland salinity (that is, not affected by modern-day seawater) stems from trapped water during sedimentation either in a saline environment or through prolonged stagnation and rock-water interaction. In irrigation areas, salinity also occurs through the combination of evaporation following poor drainage of irrigation water. In addition, the intrusion of seawater into depleted freshwater aquifers in coastal areas affects deltaic areas of the Ganges and Indus rivers, specifically Sindh in Pakistan and West Bengal in India, as well as the east coast of India, specifically the states of Andhra Pradesh and Tamil Nadu, (Mukherjee et al. 2015).

The most significant and widespread anthropogenic pollutants in the region include nitrate and microbial pathogens (Luby 2008). Lack of proper sanitation—as well as improperly placed or protected wells—can lead to microbial contamination of drinking water from shallow aquifers. Nitrate pollution is common in shallow aquifers as a result of on-site sanitation, excessive use of fertilizers, and wastewater disposal. In India, high nitrate levels in groundwater (more than 40 milligrams per liter) have been reported in 387 districts in 21 states (CGWB 2014). The health impacts of pollution (see table 3.3) are strongly linked to poverty. In areas contaminated by fecal material, the economically disadvantaged often lack access to potable drinking water (Luby 2008). Contaminated water supplies are also major social and economic concerns, affecting human capital and workforce productivity across much of the region.

Poor groundwater quality undermines the strategic value of groundwater as a resource for climate adaptation. It is also of major concern to the public and to ecosystem health. Intense groundwater abstraction may cause or increase groundwater contamination—this is the case not only for seawater intrusion in coastal aquifers but also for geogenic constituents, such as arsenic and fluoride (Garduño et al. 2011). The greatest challenge for contaminated groundwater systems is the time (that is, many decades) required to rehabilitate them and the costs incurred, to say nothing of the challenge of finding alternative water resources.

**Groundwater as a Buffer to Drought**

Drought may be characterized in four main ways: meteorological drought, hydrological drought, agricultural drought, and socioeconomic drought. From a groundwater perspective, hydrological drought reflects periods of low groundwater storage resulting from prolonged meteorological drought (Vilholth et al. 2013).

Owing to the highly variable monsoonal climate exacerbated by climate change, South Asia must increasingly strive to improve land and water management. A critical aspect is to manage water storage because of exaggerated variability created by climate change and extreme events. In this regard, both
constructed storage (that is, dams, reservoirs, and tanks) and natural storage (that is, aquifers, wetlands, lakes, and floodplains) are critical to ensure reliable water supplies for agricultural, domestic, and industrial users as well as to achieve environmental services (McCartney and Smakhtin 2010). Most available natural water storage lies not above the ground but below, in the form of aquifers, where the storage capacity is usually vast (Tuinhof et al. 2005). A striking example is the immense storage capacity of the IGB aquifer system—in excess of 30,000 cubic kilometers within the upper 200-meter sequence, a volume nearly 100 times larger than all constructed surface storage in the South Asia region and more than 20 times the annual combined flow of the Indus, Ganges, and Brahmaputra rivers (MacDonald et al. 2015). Although most of this water cannot be directly or sustainably exploited, the figures illustrate the relative sizes of natural water storages.

In times of drought, groundwater resources can provide emergency relief and ongoing water supplies for critical purposes because they are often better buffered against hydroclimatic variability than surface waters (Pavelic et al. 2012; van Steenbergen and Tuinhof 2010). From the perspective of the highly monsoon-dependent agricultural systems of South Asia, the buffering role of groundwater operates across a range of time scales: short term in coping with a delayed start of the monsoon or with dry spells during the monsoon; medium term in coping with failed monsoons; and long term in coping with multiyear droughts. Furthermore, in irrigated areas with limited reservoir storage, groundwater provides the standard alternative source for dry season cropping when canal water supplies are very limited or nonexistent. These are key aspects that underpin the unique and strategic value of groundwater if it is well managed.

The buffering capacity of South Asia’s groundwater systems is illustrated schematically by figure 3.3.

**FIGURE 3.3. Comparison of Effects of Hydrological Drought**

![Comparison of Effects of Hydrological Drought](image)

*Source: Authors figure.*
The depletion effect of drought on aquifers is less pronounced than that of surface water. However, this buffering capacity is not unlimited, and depends on local hydrogeological conditions and groundwater abstraction volumes.

Although both have a greater buffering capacity than surface water, aquifers with high storage capacity (a function of both physical dimensions of a system and its internal characteristics, such as permeability, as seen in regionally extensive alluvial aquifers) have dampened responses in terms of both timing and magnitude as compared with those of aquifers having low storage capacity (that is, most hard rock aquifers). The adaptive capacity of hard rock aquifers is constrained by low storage capacity and limited residence time of groundwater in these aquifers (Fishman et al. 2011; Kulkarni, Shah, and Shankar 2015; Pavelic et al. 2012). Otherwise, buffering may be considered a means of enhancing resilience, which depends on the physical, chemical, and hydrogeological parameters of an aquifer, and on the long-term recharge (Foster and MacDonald 2014).

Studies from the region show the buffering value of groundwater in practice. Palanisami et al. (2012) found that in tank-irrigated areas of the Indian state of Tamil Nadu, the economic value of groundwater drawn from crystalline aquifers ranged from 15 to 19 percent of the total value of irrigation when used as a supplementary water source. Pavelic et al. (2012) examined rainfed and irrigated parts of the upper Bhima River basin in the state of Maharashtra, India, and found that local communities relied more on groundwater from basaltic aquifers during three consecutive years of drought (2001–03) than at other times. After drought, groundwater levels that had declined to the lowest recorded quickly returned to predrought levels. Chinnasamy, Maheshwari and Prathapar (2018) developed the Groundwater Resilience Index (adapted from the Standardized Precipitation Index commonly used to assess meteorological droughts), which they applied to intensively used hard rock aquifers in the states of Gujarat and Rajasthan. This showed that variability in the groundwater index was less than that in the precipitation index, highlighting the buffer value of groundwater.

Further illustrating the importance of water storage, Fishman et al. (2011) analyzed how shallow hard rock and deep alluvial aquifers respond differently to intensive groundwater use by agriculture. In the crystalline granites of the Indian state of Telangana, groundwater (both in terms of storage and replenishment) was the critical factor for exploitation. However, in the alluvial aquifers of Punjab, where long-term groundwater declines are evident, energy and land, rather than water per se, were the key constraints. This study also revealed how groundwater-dependent agricultural economies are sustained in different hydrogeological settings and the importance of drivers that lie outside the water sector. These findings align with qualitative assessments made by Shah (2012).

The widespread use of groundwater by South Asia’s farmers is, in itself, an adaptive approach because it has reduced the vulnerability (and subsequent risk) that rural communities experience in times of drought. Crop loss is one such risk (Moench and Dixit 2004). Reducing this risk by accessing a reliable water source, such as groundwater, encourages farmers to invest in fertilizers and other inputs and, consequently, to generate surpluses far more consistently than when they depend only on rainfall or on irrigation from surface water. This situation is effective until resource use becomes unsustainably high. A combination of long-term groundwater overexploitation and drought can lead to the drying up of wells, negatively affecting livelihoods that depend primarily on agriculture. This situation was common across drought-prone parts of the region during major droughts in 1987, 2002, and 2015.

The lowest rainfall areas are found primarily across the western corridor of the Indian subcontinent, characterized by low rates of recharge and high drought frequency (map 3.7). Areas that need groundwater the most for climate adaptation are often the same areas
where drought frequency already is high and where groundwater depletion is greatest. This presents a significant challenge for groundwater management and positions groundwater centrally within regional strategies to adapt to climate change.

**Climate Change and Groundwater**

The effect of climate change on groundwater recharge in the South Asia region is difficult to predict, and it needs to be understood in the context of ongoing effects of changes in extraction patterns over the past 100 years. While groundwater systems in the region have yet to establish a new equilibrium in response to these changes, climate change is also starting to have an effect. The region already experiences significant variability in climate, and changes in rainfall intensity and timing, elevated temperatures, and resultant changes in agricultural cropping practices will combine to influence patterns of groundwater recharge and usage. Concurrent demographic changes and increasing urbanization may exert equally noteworthy influences. In general, recharge fluxes depend highly upon

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**MAP 3.7. Drought Frequency in South Asia**

Note: Derived from NDVI data with a normalized range for each pixel such that a value of 0 means “no drought ever detected” and 1 is “drought was detected continuously” over the period from 2001 to 2013.
precipitation because aquifers of the region are recharged mainly by precipitation and through interaction with surface water. However, changing intensity of rainfall, rates of sediment transport, and meltwater flows make any attempt to infer the effects difficult. With more extreme events, flooding could enhance recharge during intense and short-term events (Taylor et al. 2013). Recharge has a role for river flows in many lowland areas fed by groundwater discharge, which is especially important during the dry season.

In areas where irrigation dominates recharge, changes in the availability of groundwater will relate directly to changes in irrigation. If managed appropriately, such changes can lead to positive long-term outcomes (van Steenbergen 2019).

Storage characteristics of a groundwater system contribute significantly to its responsiveness to drought and to the timing and duration of that response (Van Lanen et al. 2013). Similarly, estimates of time lags in response to changes in climate, exhibited in different groundwater systems, show that these are variable and should be considered when planning strategies for adapting to climate change that place greater reliance on groundwater (Cuthbert et al. 2019).

Notes
1. An agrowell is a shallow lined or unlined dug well used for agriculture.
2. The Central Groundwater Board (2017) consider nonsafe areas to have a stage of development (that is, extraction relative to recharge) of at least 70 percent and long-term declines in trends of groundwater levels before a monsoon and/or after a monsoon. These nonsafe areas are further differentiated into three classes: semicritical, critical, and overexploited.
3. Based on the proportion of nonsafe administrative blocks relative to the total number, scaled according to the total area.
4. To read the blog post about groundwater depletion and its effects on impoverished people, go to https://wle.cgiar.org/thrive/2014/06/10/when-wells-fail-farmers%E2%80%99-response-groundwater-depletion-india.
5. Geogenic contamination of groundwater refers to naturally elevated concentrations of certain constituents. Anthropogenic contamination comes from human-related activities.
6. The WHO standard for arsenic in drinking water is 10 micrograms per liter. However, because of the practical difficulties in removing arsenic from water, many South Asian countries set a permissible limit of 50 micrograms per liter.
7. Tanks are large or small reservoirs or ponds common to peninsular India and Sri Lanka; they often were constructed many centuries ago.
Chapter 4
Groundwater Governance in South Asia

Groundwater is an intrinsic part of social, political, and economic activities; thus, decision making outside the water sector affects it. Governance issues are complex and multifaceted because they span administrative units and scales (districts, international boundaries, provinces, states, towns, villages); diverse hydrogeological environments (alluvial, coastal, hard rock); human settlement domains (rural, urban); political economies (countries, policies, political parties, programs); and sectors and their institutions (agriculture, energy, environment, health, industry, water).

A broad consensus exists on the need to strengthen groundwater governance across South Asia. However, there is far less clarity on how to achieve this. Institutional inertia impedes rapid progress on alternative solutions and coping strategies, which could lead to more sustainable outcomes. In addition, political incentives to prevent gradual and possibly irreversible damage in the long term usually do not exist. This is because groundwater lies out of sight. Although it is replenishable and amenable to effective management and protection, it is also vulnerable to long-term (intergenerational) and practically irreversible effects if managed poorly (Villholth et al. 2018).

This chapter reviews four key aspects of groundwater governance: actors and institutions; information and science; policy and plans; and legal frameworks. Three common trends in groundwater governance in South Asia are evident: (a) the challenge inherent in managing millions of small-scale groundwater users, especially when institutions have limited, fragmented, or overlapping mandates; (b) some positive steps in developing policies to guide groundwater management; and (c) shared limitations of laws and regulations that have lagged behind advances in science and policy, leaving water managers with limited mandates and relatively few legal or regulatory tools to better manage groundwater.

Multitudes of Actors and Fragmented Institutional Mandates

Groundwater—a common pool resource accessed by many users yet hidden from view—is widely acknowledged to be much easier to develop than to regulate and protect (GGP 2016; Giordano 2009; Kemper 2004; Villholth et al. 2018). It is no different in South Asia, where groundwater development over the past half century has largely been unplanned, unregulated, and unmanaged. During this boom period, the attraction of groundwater for millions of users lay in the absence of all administrative controls. Although groundwater institutions and policies have actively supported this trend, so too have energy subsidies. Across much of South Asia, the price of energy applied to groundwater irrigation (a surrogate for a water price) has failed to relate to the abundance or scarcity of groundwater. These elements have played a large part in defining the state of governance and emergence of the tragedy of the commons.

Accordingly, groundwater management in South Asia is very challenging because the groundwater economy lies largely in the hands of hundreds of millions of private users (Shah 2009a). Moreover, endowment of groundwater is unevenly distributed, and most users are small scale and scattered. Competition for the resource is high, particularly with regard to hard rock aquifers, which have the most apparent resource constraints. Small land holdings mean that well densities are also high; thus, well interference is common. Similarly, different groundwater abstraction technologies interfere with one another. Deep tubewells and
higher-capacity pumps of wealthier farmers can affect the yields of shallower wells owned by less affluent farmers. All these factors combine to complicate the enforcement of legal arrangements to control groundwater use. In addition, South Asian governments probably have been reluctant to implement punitive measures to restrict groundwater development and extraction because such measures are highly unpopular with the large vote bank of smallholder farmers (Closas and Molle 2016).

Furthermore, the institutional frameworks of many South Asian countries complicate efforts to sustainably manage groundwater use. Often, multiple public institutions list at least some functions relevant to groundwater management. This increases the possibility of duplication, gaps, lack of clarity, and uncoordinated efforts. For example, in Sri Lanka, institutions with functions relevant to groundwater management include the Central Environmental Authority; the Mahaweli Authority; the Irrigation Sector of the Ministry of Agriculture, Livestock Development, Irrigation and Fisheries and Aquatic Resources Development; and the Water Resources Board. These national complexities become even more challenging in the context of managing transboundary aquifer systems in South Asia—where the number of stakeholders is increasing but mandates and institutional arrangements for them typically do not exist. Overall, such complex institutional arrangements often reflect weaknesses in the legal framework—mandates for key water management activities are not clearly spelled out. As discussed further in the “Groundwater Policy—Recent Advances” section, improvements to the legal framework can help clarify institutional mandates and roles.

This institutional picture can be even more complicated in large decentralized federal systems, such as India and Pakistan; complexities abound at both the federal and state or provincial levels. For example, according to India’s constitution, the central government’s mandate focuses on regulatory oversight and provision of technical support to states. India’s Ministry of Water Resources, River Development and Ganga Rejuvenation plans development of groundwater resources. Within the ministry, the Central Ground Water Board and the Central Ground Water Authority regulate and control development. The Authority primarily issues certificates for groundwater use by industries, infrastructure, and mining projects under the Environment (Protection) Act of 1986. Many agencies in other sectors have mandates relevant to groundwater, notably the ministries governing agriculture, power, and rural development. However, in India, primary responsibility for groundwater management lies at the state level, so this complicated federal system overlays an equally complicated state system. At the state level, some, but not all, have dedicated groundwater authorities, but in almost every case, these agencies suffer from understaffing, lack of institutional capacity, and an environment that prioritizes infrastructure development ahead of resource management. Thus, across South Asia, institutions charged with groundwater management maintain a tradition to support infrastructure development but not to manage resources.

Information and Science—Essential Groundwater Data

A core aspect of groundwater governance is the collection and curation of data that underlie the scientific understanding of groundwater systems. Without accurate data and knowledge, efficient management and decision making are impossible. Because groundwater flows slowly (compared with surface water), good management relies on long-term data sets that reveal trends over time. An ability to make comparisons spatially and across different time scales (seasonal, annual, interdecadal, and longer) helps managers understand causes and predict trajectories of change in the level and quality of the resource; in addition, this ability enables appropriate governmental actors to manage these changes.
Although data sets for national and regional climate are available, it is more difficult to access those for water—and data for groundwater are rarer still. Data sets tend to be discontinuous in both spatial and temporal senses. Across the region, there are many instances of absent or incomplete data, arising either from inadequate monitoring systems or from poor or undocumented data storage. In many cases, groundwater data are fragmented among several government agencies, and sometimes access is impeded by layers of bureaucracy or by a lack of people who know where to locate and retrieve the data. Yet since the 1990s, governments in the region have made increasing efforts to achieve more effective governance of groundwater through the collection, storage, and dissemination of regional data sets that facilitate groundwater planning and management. India has several ongoing efforts. For instance, the Indian government has been posting online time-series groundwater level data from the Central Ground Water Board’s monitoring network, and some of the country’s state governments are providing similar data. Since 2012, India’s National Project on Aquifer Management (NAQUIM) has been active (see box 4.1.) Finally, the National Hydrology Project—funded equally by the government of India and the World Bank—includes a component to upgrade groundwater information and is striving to publicize water data from thousands of digital recorders.

**BOX 4.1. National Program on Aquifer Management (NAQUIM)**

In 2012, the government of India embarked on NAQUIM, part of its effort to achieve sustainable groundwater use. On a country-wide scale, NAQUIM seeks to complete the following:

- Three-dimensional delineation and characterization of all major aquifers in the country as well as assessment of their sustainable groundwater volumes and chemical quality
- Identification of suitable areas for further development or for resource enhancement through managed aquifer recharge
- Gathering and dissemination of data to water users and other stakeholders, including researchers and government agencies

On a local scale, NAQUIM examines approaches to groundwater management and develops demand-based interventions for sustainable use of groundwater in accordance with local rainfall, cropping patterns, and groundwater data, and supported by participatory forms of groundwater management.

NAQUIM’s target is an area of about 2.6 million square kilometers, representing 80 percent of the country. Researchers are using state-of-the-art techniques in geophysical exploration, isotopic analysis, and groundwater flow modeling in addition to more established investigation methods (Saha, Marawaha, and Dwivedi 2019). Pilot projects in six states have established the efficacy of the techniques to be adopted and framed protocols for future investigations.

As of 2018 NAQUIM has completed about 0.7 million square kilometers, extending across different aquifer types and across multiple states of India.

Source: Saha, Marawaha, and Dwivedi 2019.
Groundwater Policy—Recent Advances

Until the late 1990s, groundwater management was not a major focus of policy development in South Asia. This is changing, however, and table 4.1 highlights regional examples. For example, groundwater merits only a brief mention in India’s 2012 National Water Policy, although it figures more prominently in Bangladesh’s 1999 National Water Policy, particularly with regard to objectives for the agricultural water use sector. Globally, groundwater governance receives

<table>
<thead>
<tr>
<th>Country</th>
<th>Policy instrument</th>
<th>Groundwater relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water sector policy under development (Haidary 2018)</td>
<td>To be determined (policy under development)</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>National Water Policy (1999)</td>
<td>The policy recognizes groundwater challenges. Policy objectives include promoting groundwater development for irrigation. It states that for “sustaining rechargeable shallow groundwater aquifers, the Government will regulate the extraction of water in the identified scarcity zones with full public knowledge” (page 8).</td>
</tr>
<tr>
<td>Bhutan</td>
<td>Water Policy and Water Vision (2007)</td>
<td>Groundwater merits a brief mention as a potential alternative water source that should be protected in view of its possible future use (page 14).</td>
</tr>
<tr>
<td>India</td>
<td>National Water Policy (2012)</td>
<td>Groundwater challenges receive brief recognition (page 2). The document states a few related policy objectives; for instance, “the over-drawal (sic) of groundwater should be minimized by regulating the use of electricity for its extraction” (page 7).</td>
</tr>
<tr>
<td></td>
<td>National Water Supply and Sanitation Sector Policy (2014)</td>
<td>Groundwater contamination merits brief recognition as a challenge (page 11), and groundwater protection is mentioned as a policy objective (pages 16–17, 22).</td>
</tr>
<tr>
<td>Pakistan</td>
<td>National Water Policy (2018)</td>
<td>Groundwater considerations are woven throughout the policy, and a dedicated section outlines eight priority objectives for groundwater management (page 21).</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>National Policy on Protection and Conservation of Water Sources, Their Catchments and Reservations (2014)</td>
<td>Groundwater receives recognition as an important water source (page 2). The policy highlights salinization as an important challenge (page 3) but includes no specific policy objectives.</td>
</tr>
</tbody>
</table>

Source: authors analysis.
little attention until groundwater users experience major negative effects (Tuinhof et al. 2003). However, to protect the region’s vast and important resources, it is necessary to shift the focus from developing groundwater as a resource to looking at the broad picture of effective groundwater governance. Whether it stands alone as a policy document or constitutes part of a broader water policy, a comprehensive policy framework for groundwater management recognizes the inherent challenges and articulates objectives clearly.

These objectives must be consistent with a modern understanding of groundwater resources; tailored to a country and its capacity for implementation; and clearly linked to a country's broader policy goals for development. If so, they can help determine principles for all institutions and sector actors in addition to establishing guidelines to be implemented through legislation and regulations.

Pakistan provides one of the most up-to-date examples of policy development to improve groundwater management. In response to deteriorating groundwater quality and lowering water tables, Pakistan’s 2018 National Water Policy includes a dedicated section with eight priority objectives to guide groundwater management. A key aspect focuses on improving the knowledge base through better surveying and monitoring of groundwater resources. However, groundwater management is largely a provincial subject under the constitution of Pakistan, so the National Water Policy does not go much beyond encouraging provincial governments to take responsibility for regulating groundwater abstraction and enforcing legislation. However, the quality and comprehensiveness of legislation to be enforced varies widely across Pakistan’s provinces as does the capacity to implement necessary policy modifications and management interventions. For a regional discussion about the legal precepts that lack adequate tools for water managers and hamper implementation of these policies, see the next section on “Weak and Antiquated Legal Frameworks.”

Weak and Antiquated Legal Frameworks

On a global perspective, South Asian legal frameworks for water resources management tend to be among the least comprehensive for the management of both groundwater and surface water. Water managers in South Asia have few legal and regulatory tools to manage the resource and the millions of competing water users. In fact, the difficulties associated with characterizing and monitoring conditions of groundwater resources constitute some of the most fundamental reasons for the poor state of the resources. Yet across the South Asia region, few legal provisions support routine surveying and monitoring of groundwater, let alone releasing information for water users. Even when legal frameworks address this aspect, they often take a discretionary or advisory approach. In fact, legal frameworks for water resources management in South Asia primarily focus on basic institutional setup, rather than requirements for core activities or obligations for water users, because of a reliance on historical (often colonial-era) legislation with only limited updates over time, if any.

Fortunately, some recent scattered and piecemeal advances have occurred with the introduction of basic provisions to support groundwater management. For example, in 2017, the Sri Lankan government introduced groundwater management regulations under the 1964 Water Resources Board Act. For the first time, well drillers must get written permission from the Water Resources Board before drilling new industrial or large-diameter agricultural wells. Furthermore, they must register with the board before offering drilling services, and groundwater users must install meters and submit data on water extraction to the Water Resources Board every three months. Similarly, in early 2018, Bangladesh introduced a groundwater ordinance that requires permission from the local district office (Upazila Parishad) before drilling any new wells for agricultural purposes. These introductions are important initial steps to supporting better groundwater management. However, more progress is necessary.
Many countries in other regions have more comprehensive legal provisions to support collection of information, groundwater planning, and groundwater resource protection, whether specific to groundwater or part of broader holistic water resources management.

The Need for Improved Governance

In summary, groundwater governance in South Asia has significant challenges and weaknesses. Contributing factors lie in ill-targeted policies that negatively affect groundwater (for example, subsidies for energy and for crops that require high water use) as well as in weak management typified by groundwater authorities who lack resources and institutional capacity to enforce even the most limited laws. A rapid escalation in groundwater use threatens to set back socioeconomic gains made in the region, as detailed in chapter 3 of this report. Improved governance and better management of groundwater resources are critical prerequisites for a strategic pathway to build resilience and adapt to climate change. Progress along such a pathway is contingent upon recognition that managing groundwater effectively relies as much on behavior and actions of people (that is, users of water and land resources) as it does on the water resources per se (such as recharge, abstraction and water quality). Expressed differently, the socioeconomic and political dimensions of groundwater use (demand-side management) are as important as the hydrogeological dimension (supply-side management), though integration of both is often desirable (Giordano 2009; Tuinhof et al. 2003). This approach is reflected by the government of India and the World Bank, through the planned five-year US$1 billion Atal Bhujal Yojana (ABHY)—National Groundwater Management Improvement Program, which focuses on strengthening community-based institutions to foster better management in selected states of India.

As this chapter has highlighted, improving groundwater governance in South Asia is complex. Some necessary priorities include:

- Developing better, more comprehensive policy directions for groundwater management. These directions must recognize challenges and clearly articulate goals that are consistent with a modern understanding of groundwater resources, tailored to a country, and clearly linked to broader development policy objectives for a country.
- Evaluating and possibly reforming legal frameworks to give water managers clearer mandates to improve understanding of groundwater resources, plan their management, and deal with allocation and overextraction. Legal frameworks must enable water managers and water users to deal with contamination and depletion.
- Identifying and addressing horizontal and vertical fragmentation of institutional mandates if they have negative effects on the ability to carry out core water management functions.
- Investing in improved data collection to better understand groundwater resources, their patterns of use, and the associated risks. Information can facilitate better decisions by water managers and individual water users.
A cross South Asia, there are common groundwater challenges. Since the 1990’s, depletion of groundwater has been a growing problem, becoming critical in some areas, affecting mostly poor farmers. In places, the costs associated with groundwater use become prohibitively high, the resource becomes insufficient and quality deteriorates. The mega-irrigation areas of South Asia are now settings for the twin scourge of groundwater depletion and waterlogging with secondary salinization. Communities in urban centers that are highly dependent on groundwater regularly face water crises. Geogenic and anthropogenic pollution is widespread, resulting in a legacy of impacted aquifers that are almost irrecoverable over foreseeable time frames. These issues jeopardize human health and water security and impact drought resilience.

However, not all challenges are present, or of the highest priority, everywhere. There is no single path forward for improving groundwater management across all of South Asia, and different choices will be needed in different locations. Any groundwater management interventions or groundwater governance reforms must respond to the specific challenge at hand and be suitable for implementation in light of local needs, capabilities, competing priorities, cultures, and traditions. Whereas chapters 2 to 4 of this report outlined the current situation for groundwater management in South Asia, this chapter and the next, with case study examples, will explore these factors and the processes and options for possible paths forward.

### Distilling Groundwater Challenges

Whether at the country, subnational region, or community level, framing and prioritizing specific groundwater challenges is not trivial. Neither is defining and agreeing upon the solution. The heterogeneity of groundwater systems poses a technical challenge for problem framing, which is frequently confounded by poor or absent data. In turn, these also impede the adequate design of interventions—and of the necessary monitoring and time frame to demonstrate the impact of such interventions. The best approach could be different across countries, between cities and rural areas, and among households. The same underlying challenge can be framed in multiple ways by different stakeholders, and how an issue is framed can have important consequences for determining the menu of possible management interventions when trying to address a particular challenge.

When distilling and framing groundwater challenges, process and scope matter. Many management interventions require individual households over a wide area to change their behavior in some way. Unless enforcement mechanisms are applied diligently to all users, these interventions are likely to fail when individual users do not perceive the problem the same way or its impacts to the same extent. Effective stakeholder engagement—whether through local meetings or other mechanisms for collecting views from the ground level—is an important process component that can help frame groundwater challenges and gauge popular agreement with these challenges, as well as eventual support for possible interventions.

### Identifying Options for Interventions

Rarely does one single intervention or reform solve a problem and so groundwater management interventions comprise a portfolio of approaches, broadly seeking to contain and mitigate the consequences of
intensive and unregulated resource development, prevalent across the South Asia region, by directly or indirectly managing demand and enhancing supply. Groundwater management interventions on the demand side may include the introduction of improved irrigation technologies and efficiency (Chowdhury 2010), selection of low-water-use crops (Reddy, Reddy, and Rout 2014), agricultural commodity pricing policies (Srivastava et al. 2015), and energy pricing policies (Shah 2009a). Supply-side interventions include managed aquifer recharge (Dillon et al. 2019). Application of either or both demand control and enhanced recharge result in a stabilizing or enhancing effect on aquifer storage (see figure 5.1).

The inherently heterogeneous nature of groundwater systems, even regional systems (such as the extensive alluvial aquifers of the Indo-Gangetic basin), means that management solutions can be approached at more local scales. Where a particular challenge (such as

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**FIGURE 5.1. Schematic Illustration Showing Trajectory of Groundwater Overexploitation and Subsequent Mitigation**

Source: Adapted from Dillon et al. 2009.a

Note: GW = groundwater.

a. Trajectory shows groundwater depletion during the development phase (pre-adaptation) followed by a recovery phase for groundwater levels as a result of management interventions that address the supply-demand imbalance. The impact of changing groundwater levels on agricultural productivity (non-irrigated and irrigated) and relative contributions from shallow, medium, and deep wells are indicated by the green areas in the bottom of the illustration.
Managing Groundwater for Drought Resilience in South Asia

groundwater depletion) is of widespread occurrence but localized extent, solutions in one part of the system can often be adapted to that same challenge in other parts of the same system—and to similar settings in different groundwater systems (for example, between different hard rock aquifers across the region). The extent to which they can be approached in a comparable manner depends on the nature of intervention and the similarity of the groundwater setting. These issues will be explored further in the next chapter’s included case studies.

Evaluating Options for Intervention—an Analytical Framework

Although a wide range of technical management options and potential governance reforms exist for most groundwater challenges, the appropriate choice in a given local situation will be influenced by geographical, climatic, socioeconomic, cultural, and political factors (chapter 2). One aspect that can constrain the choice of available technical management interventions is the difference between regional aquifer types. In South Asia, these can be classified into several broad categories (chapter 3). Each category has different time horizons on which they respond to management interventions, yet they all share a capacity to fulfill a role in building resilience to climate change. The natural storage plays a stabilization role in coping with mid-season dry spells, a buffering role during monsoon failure, and “carryover storage” during multiyear droughts. As indicated in “Groundwater as a Buffer to Drought” in chapter 3, the extent to which different groundwater systems can fill this role is strongly dependent on their storage capacity. The larger the storage, the greater the buffering ability and the longer it will take to recover once normal climate patterns resume (figure 3.3). Similarly, systems with larger storage will be slower to respond to management interventions. This may impact which interventions are suitable in response to urgent problems. Therefore, to assist in framing the analysis of interventions to enhance drought resilience, it serves to consider aquifers in groupings according to their broad storage and response characteristics (table 5.1).

Although important, the storage characteristics of groundwater systems represent just one of several considerations for effective groundwater management for drought resilience. Previous chapters have identified that this ability depends on several interlinked factors, including the physical setting, recharge characteristics, pre-existing state of the groundwater resource (groundwater level and quality), and intensity of usage. The heterogeneity of all aquifer systems may also impact this ability locally, including the time lag in system responses to those challenges.

<table>
<thead>
<tr>
<th>Aquifer class (refer to map 3.1)</th>
<th>Description</th>
<th>Storage characteristics</th>
<th>Indicative response characteristics (also influenced by usage intensity and recharge characteristics)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 4</td>
<td>Extensive alluvial aquifer systems (for example, IGB)</td>
<td>Large</td>
<td>Decades</td>
</tr>
<tr>
<td>5</td>
<td>Other unconsolidated aquifers (alluvial and coastal)</td>
<td>Low to moderate</td>
<td>Years to decades</td>
</tr>
<tr>
<td>6</td>
<td>Semiconsolidated/consolidated aquifers</td>
<td>Moderate</td>
<td>Decades</td>
</tr>
<tr>
<td>2, 3, 7</td>
<td>Hardrock aquifers</td>
<td>Low</td>
<td>Years</td>
</tr>
</tbody>
</table>

Source: authors analysis.
Note: IGB = Indo-Gangetic basin.
Management options for sustainable groundwater outcomes are not limited to the water sector. Just as the problem of groundwater depletion can be exacerbated by perverse incentives in other sectors (such as minimum price guarantees for high-water-use crops or the provision of low-cost electricity to agricultural communities), so can the response to the problem come from these other sectors.

This report presents a number of case studies that discuss interventions, implemented in a local context, that provide important information about available options that may be used to address specific problems. The case study approach is useful in two respects: (a) it reveals clear entry points to create positive change, backed by the available evidence, and (b) it provides a knowledge base on which to identify challenges and trade-offs to inform the wider deployment and further refinement of interventions.

The case studies in the next chapter were selected to illustrate both the scope and scale of groundwater interventions in the South Asia region and their potential for adaptation across the region. These examples address the linked issues of preserving groundwater and improving drought resilience through more sustainable, pro-poor extraction, which provide a basic framework for the case study analysis as shown in table 5.2. Both aspects are affected by cross-cutting issues such as groundwater pollution.

Scale matters when deciding among possible responses to groundwater challenges. As the scale for implementation expands beyond pilot projects, supporting institutions, policies, laws, and regulations (and the gaps therein) begin to matter more and more. The current institutional landscape and the state of laws and regulations may effectively preclude some management interventions in some local and country contexts. For example, existing gaps in laws or regulations may not provide adequate power for local authorities to prohibit the drilling of new tubewells in an area of extreme overextraction. Alternatively, from the institutional perspective, the relevant government entity tasked with enforcement may not have adequate budget, staff numbers, or capabilities to effectively enforce such a rule in practice. Thus, options for management interventions must be considered in the context of the authority and capacity of the implementing agency.

Recognizing and Supporting Adaptive Learning

Improving groundwater management across South Asia will require an iterative process of trial and error and adaptive learning over time—including a range of both technical management interventions and improvements in governance aspects. Some chosen options for intervention or reform will fail, and it

<table>
<thead>
<tr>
<th>Preserving groundwater focus</th>
<th>Sustainable, pro-poor extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Community action to control groundwater depletion</td>
<td>• Pro-poor public well development</td>
</tr>
<tr>
<td>• Enhancing groundwater resources through managed aquifer recharge</td>
<td>• Protecting traditional systems</td>
</tr>
<tr>
<td>• Conjunctive management to mitigate depletion, waterlogging, and secondary salinization in major irrigation areas</td>
<td>• Energy sector initiative: solar irrigation pumps for poverty alleviation</td>
</tr>
<tr>
<td>• Energy sector initiative: solar irrigation pumps—pricing initiative for groundwater preservation</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cross-cutting issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Pollution: including regional diffuse pollution, urban and/or point source pollution, and seawater intrusion of coastal groundwater</td>
</tr>
<tr>
<td>• Ecosystem service decline</td>
</tr>
</tbody>
</table>

Source: authors analysis.
will be necessary to learn from these and move on accordingly. This is particularly likely considering that decisions are made in an environment of significant uncertainty. As highlighted elsewhere in this report, data on groundwater in many areas are limited or nonexistent and the demand for groundwater is changing over time, as is its ability to replenish. These changing conditions can alter the contours of problems, their relative priorities, and feasible responses. Similarly, problems can change in geographic scope over time. For expanding problems, significant adaptation is often required when moving groundwater management interventions from the limited pilot stage to wider geographic application.

Finally, when it comes to the governance side, it is important to recognize that legal frameworks can sometimes pose inherent challenges for iterative adaptation in groundwater management. In many countries, the law-making process—and even the regulation-making process—can be politically complex and time consuming. Reform processes regularly take years or even decades, even if there is recognition that something is not working or is not implementable. Thus, choices made in laws and regulations can have long-lasting impacts.
Governments, nongovernmental organizations (NGOs), communities, and individual water users across South Asia are trying a wide range of practical interventions in hopes of better managing their groundwater resources. This chapter highlights nine case studies from across the region (eight of which are documented in more detail, separately) identifying their main features. They provide examples of interventions in relation to geographic areas, aquifer types, and local contexts. Each case study involves one or more forms of intervention, and together, they offer a mix of well-established and novel ideas. More details on eight of the studies appear in background papers (see appendix A).

**Community-Based Groundwater Management in Andhra Pradesh, India**

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsustainable groundwater use leading to:</td>
<td>Demand management by outreach and education</td>
</tr>
<tr>
<td>• Declining groundwater levels and</td>
<td>• Formation of groundwater management committees</td>
</tr>
<tr>
<td>• Low resilience to drought</td>
<td>• Restrictions on new tubewells</td>
</tr>
</tbody>
</table>

India’s largest and best-known example of participatory groundwater management is the Andhra Pradesh Farmer-Managed Groundwater Systems (APFAMGS). Implemented by local NGOs and supported by international donors, the project spanned nearly two decades (1995-2013) and extended across 500 villages in seven districts of Andhra Pradesh and Telangana (Reddy and Reddy 2019). The region has a high proportion of vulnerable populations with regard to caste, literacy, and poverty, and it is also characterized by hard rock aquifers, moderate rainfall (600 to 1,000 millimeters per year), and high vulnerability to drought. The main objective of APFAMGS was to promote sustainable groundwater management by building awareness about groundwater resources at the community level.

The project’s founders believed that proactive engagement would bring about positive behavioral change through voluntary self-regulation. They focused on educating well owners and training them in water monitoring and crop water budgeting so that farmers could plan each season’s crops based on water availability. Farmer water schools were established to provide this training and to support the sharing of information. Plans were prepared by Groundwater management committees that had been established as new village-level institutions. Further efforts to manage demand included the promotion of micro-irrigation and discouraging the planting of water-intensive crops, such as paddy rice.

Overall, project results were mixed. On the positive side, the area shifted to less-water-intensive crops. Before the project, many farmers used flood irrigation to grow paddy rice and groundnut crops. Most farmers shifted to horticulture crops during the 2002-04 droughts and did not return to paddy cultivation. Field visits showed farmers transitioning from sprinkler to drip irrigation. Greater awareness of groundwater’s vulnerability helped farmers adopt new forms of intervention and adjust to markets. Despite these achievements, monitoring data suggest no discernible improvement in local groundwater conditions. Over the project period, rainfall has marginally declined, and groundwater demand has increased rapidly because of greater dependence. In the absence of external support, the community has not maintained initiatives for monitoring and physical infrastructure, although crop diversification has continued.
Government regulations complemented the community-based approach of the project. Supported by government and bilateral agencies in Andhra Pradesh, APFAMGS integrated a knowledge-based approach with regulatory enforcement to manage groundwater. The concerted effort ended tubewell drilling, increased the cultivated area, provided protective irrigation during critical periods, and led to some improvement in water distribution, though inequity in water access continues to be a serious issue. Because of shifting underlying conditions, the project’s participatory groundwater management likely had a limited effect on water resources, but greater awareness and complementary regulatory actions helped communities better adapt to droughts.

Box 6.1 gives another example of participatory management.

**Urban Community-Led Initiatives in Bhuj, India**

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Interventions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapidly declining water levels in public wells</td>
<td>Formation of community water conservation associations</td>
</tr>
<tr>
<td>Increasing salinity</td>
<td>Managed aquifer recharge</td>
</tr>
</tbody>
</table>

The existence and prosperity of Bhuj, India (population 250,000), is intertwined with management of its scarce freshwater resources (CEPT University 2017). The district capital of Kutch in the state of Gujarat, Bhuj lies in the southern part of the great arid zone of western India between two ephemeral rivers (Khari and Nagor). It has a mean annual rainfall of 370 millimeters (1901-2013) over eight to 14 days. The city grew from a small habitation in 1510 to a thriving urban center in the twentieth century. For its water supply, Bhuj relies on the semiconsolidated Bhuj Sandstone, which forms an excellent aquifer system reaching a depth of 250 meters. Groundwater quality is marked by high iron in places, and salinity generally increases with depth (Biswas 1987). City water supplies traditionally have depended on dug wells sustained by a system that spans more than 40 square kilometers and consists of lakes intricately connected via dug canals, natural streams, and tunnels. The entire network was engineered to feed the highly prized Hamirsar Lake, with overflow passing downstream to Pragsar Lake. In the earliest years of organized municipal water supply (1968), water was pumped from a network of 14 dug well stations (20 to 25 meters deep) at different locations. As the city grew, dug wells gave way to tubewells tapping deeper zones, and by 1986, the municipal supply depended completely on tubewells.

Following a devastating earthquake in January 2001, the government invested heavily to rebuild the city as a
commercial and industrial hub. Rebuilding took advantage of access to the sea and the promise of water from the Sardar Sarovar Dam on the Narmada River, about 400 kilometers to the east. However, increasing city demand strained water supplies, and more municipal tubewells were sunk into the Bhuj Sandstone to fill the shortage. Groundwater levels declined quickly, and higher-capacity pumps tapped deeper zones. Privately owned tubewells also mushroomed within the urban area in the absence of regulation on well construction.

Rapidly declining water levels and rising salinity in and around Bhuj—combined with frequent monsoon failures since 2001—triggered community interest in groundwater management. As of 2018, the Bhuj municipality supplies about 31,000 cubic meters per day of water, 80 percent of which comes from the Sardar Sarovar Dam and the remaining 20 percent from two wellfields 12 kilometers outside the city. Between 1971 and 2018, the water level dropped in these wellfields by more than 150 meters. At the same time, salinity, as measured by total dissolved solids (TDS), increased by more than 1,000 milligrams per liter, and the high iron content was leading to frequent well failure. Approximately 240 private dug wells (20 to 30 meters deep) and tubewells (80 to 150 meters deep) also operate within the urban area, extracting an additional 2,300 cubic meters per day with TDS values as much as 3,000 milligrams per liter. Across the urban area, the rate of water level decline (0.8 to 1.2 meters per year) is lower than in the wellfields (2 to 2.5 meters per year) because of lower well density and additional recharge through leakage from lakes and water supply pipes. As of 2018, municipal water is available once every four days, and many new residential colonies have no water supply.

Renewed efforts are occurring at the community level to revive traditional water-harvesting systems and to recharge the aquifer. In 2007, the community formed Jalshroat Sneh Sambardhan Samity (Water Resources Conservation Lovers Association), by drawing members from civil society via the mentorship of a local NGO (Arid Communities and Technologies). Under this association, four dedicated groups look after the three watersheds feeding Hamirsar, Pragsar, and Desalsar lakes and the peri-urban areas. They handle overall planning, mobilization of funds, and efforts to sensitize inhabitants, officials, and public representatives in the city. These activities receive support from a local youth group, trained to assist. One outcome has been the installation of managed aquifer recharge (MAR) pits and wells at Jubilee Colony that recharge about 460,000 cubic meters in a normal monsoon year. Residents are responsible for maintenance costs. The water conservation group is also mobilizing the community to seek self-sustained water supplies in areas not covered by the municipal water supply. For example, the Shivra Mandap Water Association revived a defunct dug well and installed a distribution system for 115 families for year-round water supply. The youth group regularly monitors the water level and quality, and a monthly contribution from each family goes toward maintenance.

Although the Sardar Sarovar Dam provides a major portion of the water supply for Bhuj, the community recognizes the critical role of groundwater, particularly in years of limited rainfall (ACT 2017). It is becoming increasingly clear that because of Bhuj’s population and its water demand, new management must close the loop on the water cycle. The revival of water harvesting systems also is necessary, including investment in infrastructure for recharging the Bhuj Sandstone aquifer. Managing discharges of municipal and industrial wastewater and managing disposal of urban solid waste also are important, but such endeavors have not yet become a priority in Bhuj. Other practical options include treatment, storage, and strategic reuse of wastewater; structures to harvest rooftop rainwater; and improvement in system-level water use efficiencies. This case offers hope for positive change by illustrating that local communities are willing to address severe water scarcity. Similar lessons appear in the case of Hiware Bazar from Maharashtra, India (see box 6.2).
A village of about 1,300 people, Hiware Bazar, exemplifies long-standing self-regulation of groundwater resources. The village is in the drought-prone Ahmednagar district of Maharashtra, and it is underlain by the Deccan Traps basalts. For more than two decades, Hiware Bazar has followed a careful plan for watershed management and groundwater conservation that has helped the village prosper over time.

Key to its success is strong local leadership that has motivated the community and fostered links with multiple stakeholders, including government. Effective village governance has brought about positive developments, including:
- Banning tubewells for irrigated agriculture (use for domestic water supply is permitted);
- Mobilizing the community through education and awareness to move away from water-intensive crops and to limit dry season irrigation, based on annual water availability; and
- Securing investments and advice for crop diversification and groundwater recharge.

Although it would be difficult to replicate the Hiware Bazar model, successful leadership and well-designed policies could coordinate farming activities and maximize water benefits for a community.


Large-Scale Groundwater Recharge Programs in Four Indian States

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater depletion affecting drought resilience</td>
<td>Managed aquifer recharge and irrigation tank desilting</td>
</tr>
</tbody>
</table>

Faced with groundwater depletion, the chief ministers of four drought-prone states in India have initiated programs to augment groundwater recharge, helping farmers better cope with droughts (Verma and Shah 2019). In Gujarat, large-scale recharge efforts started in the late 1980s; since then, efforts have evolved and matured. In 2014, the Maharashtra government launched a five-year mission to widen and deepen rivers, desilt tanks, and harvest water to make the state drought-proof by 2019. In Telangana, India’s youngest state, the government has invested heavily in desilting and reviving irrigation tanks built by the Kakatiya dynasty between the twelfth and fourteenth centuries. Similarly, in 2016, Rajasthan initiated a campaign to make villages self-reliant in meeting water demands. Each of the four state programs has followed a unique trajectory with roots in the agrarian distress caused by consecutive years of drought. The strong groundwater component of each program illustrates that state governments recognize the critical role groundwater plays in improving drought resilience. Between the four states, strategies vary as to the specific intervention and level of community engagement and participation, also in the level of funding, program delivery and effectiveness.

Results in the four states have been mixed. Field studies from Gujarat report positive outcomes in augmenting groundwater recharge through community efforts and centralized public investments since 2004. Managed aquifer recharge in the other three states began in the mid-2010s, so it is difficult to determine or predict their effects. In Maharashtra, the approach has improved water availability in many villages (Anvesha et al. 2017), and government initiatives have attracted support from civil society and
village communities. However, field studies indicate considerable variability in implementation and village effects. In Telangana, Mission Kakatiya has highlighted the role that traditional tanks can play in promoting groundwater recharge. Field studies (Shah et al. 2017) and the project’s mid-term assessment (NABCONS 2017) have indicated an increase in irrigated area. Silt removed from tank beds has been applied to farm fields, triggering reports of improved moisture retention and productivity. In addition, fish production has increased. However, as in Maharashtra, sustainability is a matter of concern. The traditional village neerghati (tank manager) disappeared with the decline in importance of tanks, and it is unclear who will maintain the tank systems after Mission Kakatiya. By the time desilting is complete for the estimated 45,000 tanks, those covered in the first phase will be ready for another round. Policy makers will have to address who should take responsibility for ongoing tank rehabilitation. The newest initiative in this case study, Rajasthan’s water security program for villages (Mukhyamantri Jal Swavlamban Abhiyan [Chief Minister’s Water Self-Reliance Campaign; MJSA]), underscores the importance of combining technical innovations with proper monitoring of large-scale programs. Unlike endeavors in Telangana and Maharashtra, the focus of MJSA has been on small, low-cost, terrain-appropriate structures to capture surface runoff and recharge groundwater. Whereas most other programs focus on increasing water availability, MJSA also strives to improve water use efficiency. However, as in Maharashtra and Telangana, no real effort ensures that village communities take ownership of common water assets and have the capability to sustain benefits.

The broad-scale effects of implementing managed aquifer recharge projects in these four drought-prone states are encouraging with regard to government commitment and scale of programs (for example, tens of thousands of irrigation tanks in Telangana’s Mission Kakatiya). However, evidence of benefits is unavailable because not enough time has elapsed or because rigorous studies do not exist to distinguish effects of recharge from other factors. Although organizing community participation in natural resource management is challenging, Gujarat shows the importance of tapping into the potential input of farmers through supportive policies and programs. Experiences in Gujarat and Telangana emphasize that efforts to better manage groundwater fall short if perverse incentives in farm energy and cropping policies still exist. Although the possibility clearly exists for MAR across the South Asia region, a decision to emulate any of these initiatives requires adequate monitoring of their benefits and drawbacks.

Comanaging Floods and Droughts in North Gujarat and Uttar Pradesh, India

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Declining groundwater levels</td>
<td>Managed aquifer recharge (MAR)</td>
</tr>
<tr>
<td>Field damage from excess monsoon flood flows</td>
<td></td>
</tr>
</tbody>
</table>

Pavelic (2019) reports on two approaches to MAR that aim to transform hazardous floodwater into a groundwater resource, allowing farmers to sustain agricultural production and livelihoods. Both approaches seek to overcome the spatiotemporal mismatch between surface and groundwater supply and demand through targeted recharge of excess monsoon flows into depleted aquifers.

The first and simplest approach—known as Holiya—is managed by individual farmers at the plot scale to control local flooding and applies largely to semi-arid climates. It typically consists of a perforated 4-inch pipe within a concrete collection pit. The pipe typically penetrates to a depth of 8 to 10 meters, although maximum depths may be up to 25 meters. The structure is positioned in the lowest corner of a farmer's field, where it can most effectively drain monsoonal rains that accumulate because of the low infiltration capacity of topsoil.

The second approach—underground transfer of floods for irrigation (UTFI)—is more complex. It operates at the village level using retrofitted community ponds.
and recharge wells to capture and offset seasonal flood water from upstream sources in humid climates. It recharges depleted aquifers with wet-season high flows, preventing flooding and adding to groundwater storage locally as well as mitigating flooding in downstream areas. The stored recharge water may later be recovered via existing local wells for domestic supplies and intensifying irrigation.

Holiyas are reported at more than 300 sites across two districts in North Gujarat (Bunsen and Rathod 2016; Garg 2016), and anecdotal evidence suggests they are spreading into other states in India. Cost of installation is relatively low (US$40 to $540 per structure), though this may still be prohibitive for less affluent farmers. The intervention extends the duration of cultivation, increasing agricultural production by 20 to 25 percent. In areas with saline groundwater, farmers say the holiya effectively reduces salinity. In some circumstances, the holiya water is relied upon in conjunction with groundwater extraction—particularly when canal water supplies are exhausted. UTFI already has become part of government programs in Uttar Pradesh. Training for district-level officials and local community leaders reinforces both the hard and soft dimensions of UTFI—from initial siting to long-term sustainability—with the participation of farmers and local institutions. There are some similarities to existing groundwater recharge and watershed management programs in India, but these have historically targeted the most water-scarce settings and given limited attention to humid areas, where extreme seasonal excesses and scarcity are problematic.

Both approaches require adequate aquifer storage capacity for recharge, which is generally not a constraint if they target overexploited areas. The approaches offer novel ways for individuals and groups of small farmers to redress effects of floods, droughts, and groundwater overexploitation at scales ranging from farm plot to river basin. Overall, major differences between them include scales at which they operate, suitable climates, and the management applied.

Regional assessments reveal that large tracts of the Gangetic Plains are potentially suited to UTFI (Brindha and Pavelic 2016) as demonstrated by test data from a village pilot in western Uttar Pradesh. In this case, as much as 70,000 cubic meters of water can be stored underground each year, sufficient for 8 to 11 hectares of dry-season cropping. Integrated hydrologic modeling suggests scaling UTFI to the Ramganga River basin (19,000 square kilometers) would generate significant social and economic benefits by reducing floods; restoring groundwater levels and baseflows; and boosting farm production (Chinnasamy et al. 2017). Scaling up would be economically attractive, with investment recouped through financial returns to farmers within two to four years, depending on the crop.

Despite gaps in knowledge and capacity, clear potential exists for wider use of holiyas, UTFI, and similar approaches to aquifer recharge across vast tracts of South Asia, where multiple effects coincide from floods, droughts, and groundwater overexploitation. Mapping studies suggest such conditions extend across areas that support 1.4 billion people in the region (Alam and Pavelic, forthcoming). Wider implementation is conditional upon (a) enhancing scientific knowledge of how both approaches perform under a wider range of hydrogeological, agroecological, and socioeconomic conditions; (b) enhancing operational experience to build up the technical and institutional capacity needed to establish and manage these interventions sustainably; and (c) acquiring funding and political support. Administrative and institutional arrangements will likely require little adjustment to adopt the approaches in India, where government and NGOs have had watershed development projects in place for decades.

Another example of using underground storage in the region is in coastal Bangladesh (see box 6.3), and a major study in Jaipur, India, identified some of the challenges and realities of planning and realizing large-scale recharge schemes (see box 6.4).
**BOX 6.3. Underground Freshwater Storage for Water Security in Coastal Bangladesh**

The coastal polder areas of southwestern Bangladesh have abundant rainfall, but highly seasonal distribution brings acute water shortages near the end of each dry season. Several million people are believed to suffer from severe water scarcity in these areas. The United Nations Children’s Fund, in collaboration with the country’s Department of Public Health Engineering, the University of Dhaka’s Department of Geology, Acacia Water, and national partners started a pilot for managed aquifer recharge (MAR) to harvest water in the rainy season to augment freshwater storage in shallow brackish aquifers.

In the three coastal districts of Bagerhat, Khulna, and Satkhira, local laborers used local materials to set up 20 sites that draw water from nearby rooftop rainwater and ponds that then infiltrates water to wells by gravity without the need for pumping. Pilot testing from 2009 to 2012 proved successful, with each site storing approximately 900 cubic meters of freshwater per year—a sufficient amount to provide safe and adequate drinking water. MAR was cost effective, relative to other potential freshwater supplies. A scaling-up phase after 2012 boosted the total number of sites to 100. The major lessons learned from these developments include:

- Community acceptance and ownership are vital for success;
- Continued community support is needed to maintain the capacity of local beneficiaries; and
- Regular monitoring of water quality is important to ensure delivery of safe water.

This novel MAR approach may be transferrable to other coastal areas across South Asia, including peri-urban areas.

Sources: GRIPP n.d.; Tolk et al. 2014.

**BOX 6.4. A Question of Scale? Managed Aquifer Recharge and Waste Water Reuse for Jaipur, India**

In 2004, Jaipur relied on groundwater for 95 percent of its water needs, including drinking water for its 2.5 million people. A US$0.8 million feasibility study was conducted on options to address the chronic imbalance between safe yield and supply from groundwater. Studied options included creating new wellfields; using freshwater or treated waste water for managed aquifer recharge of groundwater resources; reusing waste water; or a combination of such measures.

Researchers collected and analyzed data dealing with all aspects of water resources in the Jaipur region, covering an area of almost 9,400 square kilometers. Analyzed material included both historical data and new field data describing climate, geology, hydrogeology, quantity and quality of groundwater, soil conditions, surface water, and waste water. The study also evaluated present and future demand by different users.

Analysts determined that although all options had potential to augment supply in some parts of the study area, none of the investigated solutions—nor a combination thereof—would satisfy all existing and predicted shortfalls for the entire city, thus demonstrating the relevance of scale of intervention. The study showed that efforts to address groundwater availability must include a reduction in demand for agricultural use and diversion of water from the Bisalpur Dam-Reservoir complex, constructed in the 1990s as part of an irrigation project.

Reports after 2004 indicate that Jaipur now relies on water transfers from the Bisalpur Dam-Reservoir complex for part of its water supply.

Conjunctive Water Management in Mega Irrigation Areas in Pakistan

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Proposed Intervention</th>
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<tbody>
<tr>
<td>Groundwater depletion</td>
<td>Conjunctive water management</td>
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<tr>
<td>Waterlogging</td>
<td>System modeling</td>
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<tr>
<td>Salinization of groundwater</td>
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<td>and land</td>
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Groundwater use has increased throughout Pakistan, nowhere more so than in the large canal-irrigated areas of the Indus Basin Irrigation System (IBIS), which has most of the groundwater wells, tapping the vast alluvial aquifers of the Indo-Gangetic basin (Ahmad 1995). Most groundwater use in Pakistan occurs conjunctively with surface water, except in areas not supplied by canal commands (Evans et al. 2012). In IBIS, the close connection between surface water and groundwater should be understood and managed conjunctively as a dual-resource system (van Steenbergen 2019). Conjunctive management refers to the planned comanagement of groundwater and surface water, whereas conjunctive use refers to opportunistic use of both surface water and groundwater for irrigation.

In mega-irrigation areas, groundwater levels are strongly influenced by the delivery of irrigation water from main canals. If delivery is excessive relative to demand, high rates of recharge through seepage and return flows result in waterlogging and salinization with consequences for crop production and risks of flooding. If delivery is limited, the demand for groundwater leads to depletion, and saline ingress (upward or lateral movement by saline groundwater from deeper or adjacent parts of the aquifer) can occur. The key challenge to effective conjunctive use and management requires correct balancing of irrigation water supplies between surface water and groundwater. Achieving this requires understanding the magnitude and dynamics of the resource to account for overlaps between surface and groundwater.

In the canal-irrigated areas of Punjab, Pakistan, a precarious balance exists. Recharge and discharge are more or less in balance, and waterlogging has all but disappeared in areas underlain by fresh groundwater (van Steenbergen, Basharat and Lashari 2015). Water resource managers worry that more intensive groundwater pumping will lead to deterioration of water quality; they are particularly concerned about the upcoming of poorer quality water from deeper saline layers (Alam 2014). During the past two decades, the number of wells has increased; furthermore, the proportion of wells deeper than 50 meters has increased from 7 percent in 1989 to 30 percent in 2009. At the same time, more than 2 million hectares of irrigated area have been added through conjunctive use.

In Pakistan’s Sindh province, the situation is entirely different. There, groundwater management is out of balance, with high allocations of surface water for canal command areas, and actual surface water deliveries even higher (Habib 2008). Groundwater use represents a small proportion of total water consumption, and waterlogging persists over large parts of Sindh with associated losses in agricultural productivity and related health problems for people and livestock (Solangi, Qureshi, and Jatoi 2017).

A drought period spanning 1998 to 2003 provided insights into solutions to the waterlogging problem. The drought reduced canal inflows by 12 to 25 percent. Crop production did not go down during this period; instead, it rose, a finding attributed to greater reliance on groundwater, with associated reductions in waterlogging. This finding has great importance for drought resilience and options for improved management at other times.

Efforts have taken place to conjunctively manage surface and groundwater in the IBIS, particularly via investments in drainage and reuse (Habib 2008). The area needs more, though, particularly for Sindh, where benefits would be significant: decreased flood risk; freeing up of surface water; improved health,
sanitation, and water supply; and reductions in water-logging. Moving toward a conjunctive management regime in the IBIS requires a shift in state water policies and operational plans of irrigation departments. A priority must be comprehensive water resources planning with a focus on promoting wider and planned conjunctive use and management of surface and groundwater. Achieving this would require: properly understanding the water resource base, its use and the interconnectivity between surface water and groundwater; then managing groundwater recharge, storage, and discharge accordingly; protecting groundwater quality; and managing groundwater demand. It would also require modifications to operating procedures as well as to allocation and access rules of surface water systems; better use of saline water; improved efficiency of field water use; recalibration of the severely outdated irrigation duties in the canal system; and selected investments in drainage and canal lining where appropriate. These investments would pay healthy dividends for water users and create a more resilient water regime.

Across the region, conjunctive management of surface and groundwater in the mega-irrigation systems of South Asia offers one of the most powerful strategies to sustain the water resource base while optimizing the multiple benefits of its use. Unmanaged forms of conjunctive use of surface water and groundwater are a reality within the large-scale irrigation schemes of South Asia. Advancing toward conjunctive management of surface water and groundwater resources is critical for drought resilience and for optimizing available water for agricultural productivity, using the large natural storage in these systems to offset uncertainties in surface water delivery and reduce growing pressure on groundwater resources. Conjunctive management would also help mitigate disparities in water delivery between head and tail reaches of command areas and, thereby, improve equity.

Adjusting scheduling practices from delivering water only in the dry season to delivering water during the dry season and the monsoon season could serve to irrigate fields and to recharge underlying aquifers. The water stored in an aquifer could then be recovered in the dry season. In most situations, conjunctive management would not require additional water overall to achieve significant gains in crop yields, drought resilience, and other services; however, it could add to the cost of water provision. Key to effective conjunctive management is improved system management. It would require targeted changes in infrastructure as well as capacity building, more efficient organization, and a better system of information and communication as well as more advanced planning for the use of surface and groundwater.

Two further examples of conjunctive management in India—from Andhra Pradesh and Uttar Pradesh—appear in boxes 6.5 and 6.6, respectively.

**Pro-Poor Well Development in the Barind Tract in Bangladesh**

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Intervention</th>
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</thead>
<tbody>
<tr>
<td>• Limited access to water for low-income farmers</td>
<td>• Drilling new deep tubewells</td>
</tr>
<tr>
<td>• Poor cost recovery for public tubewells, leading to inadequate maintenance and disuse</td>
<td>• Pre-paid metering</td>
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The Barind region, a water-stressed area in northwest Bangladesh, had an underdeveloped agricultural economy and high levels of poverty until a new initiative revitalized the area with enhanced groundwater irrigation (Banerjee and De Silva 2019). The Barind Multipurpose Development Authority (BMDA), a public entity in northwest Bangladesh formed in the early 1990s, established more than 15,000 deep tubewells (DTWs) in the Barind Tract. The introduction of these DTWs, combined with a prepaid smart metering system, has transformed agriculture. Cropping intensity has risen from 117 percent to 200 percent, higher than the national average of 175 percent (Jahan et al. 2010). The results have helped reduce poverty in the region from 57 percent in 2000 to 36 percent in 2010 (Jolliffe et al 2013).
**BOX 6.5. Conjunctive Management Providing Benefits in Andhra Pradesh**

In irrigation command areas where interactions between surface water and groundwater are high, conjunctive management can play a significant role in increasing water availability and improving equitable distribution of water while also maintaining long-term sustainability of groundwater resources. The Srisailam Right Branch Canal command area in a drought-prone part of Andhra Pradesh in south India offers one such example (76,900 hectares supporting more than 35,000 farmer households).

An evaluation of the effects of alternative conjunctive use strategies following release of canal water in 2004 revealed that improved water availability was quickly followed by the looming threat of waterlogging conditions in many villages and evidence of inequities in water delivery between the head- and tail-end reaches of the system. The surplus water available has high scarcity value. Through simple hydrological modeling, the spatiotemporal patterns of water surplus and deficit were identified and alternative conjunctive use scenarios assessed. By more carefully regulating canal supplies to levels that prompt sustainable groundwater extraction and by improving distribution efficiency, modeling analysis suggests that it is possible to achieve water savings of up to 48 percent of allocated water in a year that could be disbursed to downstream areas or to alternative users of higher value.

Output results could be readily interpreted to help enable informed decision making by operators and managers of the system. The conceptual and modeling framework was well received by the irrigation department.

Source: Kumar et al. 2013.

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**BOX 6.6. Piloting Conjunctive Use Management in Uttar Pradesh**

A 10-year pilot study (1989 – 1999) of the Lakhaoti Branch Canal System (part of the Madhya Ganga Canal Project) provides insights for conjunctive use management on the Gangetic Plain. The study targeted a low-cost way of using excess surface water during monsoon season for irrigation and for restoring falling groundwater levels. The program diverted 20 million cubic meters per day of monsoon water from the Ganges River through unlined earthen canals to farmers for irrigation of water-intensive monsoon crops, such as paddy rice and sugarcane, with excess irrigated water infiltrating past the root zone to the underlying shallow aquifer. Groundwater levels rose from an average of 12 meters below ground (in 1988) to 6.5 meters (in 1998), see Map B6.6.1; this is more impressive when noting that, without this intervention, analysts projected that groundwater levels would continue declining to an average depth of 18.5 meters over the study period. Annual pumping cost savings in the project area were ₹180 million (approximately US$4.2 million) with energy savings of 75.6 million kilowatt-hours per year. Farmers benefited with their average net income increasing per unit area by 26 percent through reductions in pumping cost and enhanced cropping systems (more rice and sugar under production). During the dry season, drawdown from groundwater pumping prevented waterlogging and regenerated storage capacity for recharge during the next year's monsoon. This approach has the potential to improve farmers’ livelihoods in areas where excess monsoonal flows can be harnessed by major canals overlying productive shallow aquifers.

Box continues next page
Initially, BMDA collected irrigation fees from farmers by issuing paper coupons through dealers, a cumbersome procedure that offered many loopholes for corrupt practices. In 2005–06, prepaid metering became available, and each farmer could purchase defined quantities of water from a dealer via a smart card. By 2010, this system included almost all pumps. Irrigation charges depend on the discharge rate of pumps. The system has collected 100 percent of the irrigation charges for BMDA and reduced loopholes in the system, making it a surplus-generating, self-sufficient organization. The institutional arrangements are incentive compatible, benefiting both irrigation service provider and receiver.

However, a decade after the introduction of smart metering, concerns over declining groundwater levels in the Barind area lead to questions on the sustainability and equitability of this irrigation model in light of the significant number of farmer households who depend on shallow tubewells (STWs). Socioeconomic surveys suggest significant heterogeneity regarding water security across the area (de Silva and Leder 2017), and the effects of DTWs have been assessed mainly from the standpoints of rice production and localized effects within communities served by DTWs. These exclude externalities manifested outside of DTW command areas, arising from the common
property characteristics of groundwater. Lack of evidence on the equity-related effects of DTWs on STW users suggests the need for a more comprehensive evaluation to inform future policy on DTWs within broader developmental considerations. Furthermore, the study implies that expansion of agricultural capability through publicly provided groundwater needs to occur in the context of a local water budget and a more rigorous analysis of crop water use that matches crop choice to available water.

Protecting Users of Traditional Karez Systems in Balochistan, Pakistan

Karez systems exist across the more water-scarce and drought-prone parts of South Asia, including Afghanistan, peninsular India, and Pakistan (Ashraf and Hasan 2019). The ancient Karez water supply systems of Balochistan, Pakistan, date to the Mughal empire (sixteenth century). They have long served as important sources of community water (Kahlown, Khalil, and Munir 1988; Khan and Nawaz 1995). These systems operate by tapping shallow groundwater from an upgradient motherwell, which discharges to a constructed subhorizontal tunnel that delivers groundwater via gravity to the downgradient community throughout the year. Traditionally, they have functioned even in years of rainfall deficit. In Balochistan, these were, until 1970, the cornerstone of the agricultural economy in upland areas, providing drought-resilient access to water for domestic use, drinking, and livestock as well as small-scale agriculture, especially for low-income people who lack tubewells.

Declines in rainfall, compounded by recurring droughts since the 1960s, have reduced rates of groundwater recharge so that Karez systems cannot support growing demands (Ahmad et al. 2015). To maintain their livelihoods, wealthier farmers installed tubewells, aided by energy subsidies from the provincial government (Rahman 1981). Tubewell numbers in Balochistan have increased from 5,000 in 1985 to more than 40,000 in 2014 (GoP 2016). Combined with the deforestation of catchment areas, these factors have contributed to the depletion of groundwater levels at an alarming rate (in some areas, the annual rate of decline exceeds 5 meters) as well as the reduction of functioning Karez systems. In 1970, an estimated 3,000 Karez systems existed; as of 2007, one-third still function (Ahmad 2007).

Following recognition of the Karez systems of Balochistan as World Heritage Sites by the United Nations Educational, Scientific, and Cultural Organization (UNESCO), two Karez systems (Sanjidi and Nau Sanjidi) about 30 kilometers southwest of Quetta were rehabilitated, which improved their water supply. For example, at Nau Sanjidi, discharge at the end of the system prior to distribution increased from 2.7 liters per second in 2016 to 3.1 liters per second in 2017, despite low rainfall. Rehabilitation costs were modest compared with the costs of pumping and the drilling and deepening of tubewells, which must take place every five to seven years. These rehabilitation sites also provide information to help government and other stakeholders better preserve these systems.

To safeguard the Karez as a water supply for the poorest households, a need exists to preserve and enhance these systems to help them compete with more energy- and capital-intensive alternatives. Practical steps include sound regulatory controls and enforcement to exclude tubewell drilling within the Karez recharge zones. Watershed restoration measures within these same recharge zones would enhance water availability from the Karez systems, as suggested by the rehabilitation results in the case study. High-level policy support (provincial and higher) is critical to finance rehabilitation, to increase the capacity of local communities, and to ensure compliance with regulatory measures. Cooperation of local stakeholders in rehabilitation also ranks high in importance because without it, the potential exists for social conflicts with tubewell owners—and among Karez users themselves—over water allocation.
Solar Irrigation Pumps For Poverty Alleviation on the Eastern Gangetic Plains

**Challenges** | **Intervention**
--- | ---
- Poor farmers have limited water access and consequent low crop yields | - Subsidies for solar irrigation pumps

The fertile floodplains of the Indus-Ganges-Brahmaputra basin covering eastern India, Nepal Terai, and much of Bangladesh are among the most densely populated parts of the world (Bastakoti, Raut, and Thapa 2019). Agriculture provides the livelihood of most people, but the region suffers from low agricultural productivity and arguably contains the largest concentration of rural poverty outside of Sub-Saharan Africa.

Since the late 1970s, expansion of groundwater irrigation has proved to be a powerful way to help millions of small farmers grow multiple crops on very small land parcels (less than 1 hectare). Informal arrangements for leasing land and acquiring water have made it possible even for farmers without wells to irrigate. Ownership of tubewells and pumps tends to skew toward wealthier farmers, whereas most small and marginal farmers buy water or rent pumps to meet their irrigation needs (Bastakoti et al. 2017; Jain and Shahidi 2018). Groundwater is extracted mainly with diesel- and electric-powered pumps. However, significant constraints to expanding affordable irrigation include the poor status of rural electrification as well as the high and rising cost of diesel, which powers the majority of irrigation pumps in the region. These constraints may contribute to the relative underuse of groundwater in the Eastern Gangetic Plains, although groundwater quality may also be a factor.

National and provincial governments in all three countries have been offering capital subsidies to promote the adoption of solar irrigation pumps. The number of pumps is small, but it is growing steadily, propelled by these subsidies. However, such efforts sometimes reflect a supply-side push that lacks proper considerations of farmers’ perspectives (Jain and Shahidi 2018) and they may need adjustment to ensure access to affordable and reliable irrigation for a larger number of low-income farmers. Although most government-supported promotion programs for solar irrigation pumps offer high-capital subsidies for small, individually owned pumps, some donor- and NGO-led interventions have also experimented with group pumps and the promotion of solar irrigation entrepreneurs. Each institutional model has its advantages and disadvantages, and each requires different strategies by the promoting agency in accordance with the prevailing local context and the existing level of farmer awareness about solar irrigation pumps.

The underlying risk of overexploitation of the groundwater resource must be kept in check, and the risks associated with prevalent arsenic contamination of groundwater in the Eastern Gangetic Plains needs to be factored carefully into any policy to promote groundwater irrigation in these areas.

### Solar Pumps and South Asia’s Energy-Groundwater Nexus

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<th>Challenges</th>
<th>Interventions</th>
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<tbody>
<tr>
<td>Electricity subsidies leading to: high energy costs for government and depletion of groundwater</td>
<td>Solar-powered irrigation pumps to: reduce energy costs arrest groundwater depletion</td>
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Across much of South Asia, the green revolution has gained momentum via increasingly inexpensive access to groundwater as the price of drilling and equipping tubewells has fallen continuously from the 1980s to the 2010s. Governments have supported the tubewell revolution by subsidizing energy in farming communities, which has led to uncontrolled use of groundwater and subsequent widespread depletion. Spurred by this situation, diverse pilot schemes, available as of 2018, are studied in an effort to understand the potential of solar irrigation pump (SIP) schemes to unlock the region’s perverse energy-groundwater nexus.
The study identifies that SIP pilots have been conducted in a range of groundwater settings, reflecting natural hydrogeological and climatic features as well as the groundwater status of each setting (abundance or depletion). The study analyzes risks and advantages of seven types of SIP pilot schemes—deployed across these settings—in the context of different models of promotional objectives (economic incentives at different scales) and policy outcomes. The authors evaluate the effects of pricing policies of individual pilot schemes for the extent to which they serve the poorest communities; provide appropriate signaling on groundwater availability; and reduce the burden of farm power subsidies. The schemes undergo further evaluation for their carbon footprint, scalability, and remuneration mechanisms for surplus energy. Differences in schemes reflect varying scales and capacities of installation types (from individual off-grid tubewell pumps to large-scale solar farms); types of remuneration for SIP adopters; and user access to electricity.

Individual pilots show promise, and the authors suggest which schemes work best in particular settings and scales. However, although researchers have acquired important insights, not enough data exist as of 2018 to conduct a complete analysis of effects. Although these pilots aim to reverse the perverse incentives in energy policy, potential for poor outcomes (including further depletion of groundwater) in scaling up these pilot schemes remains a risk.

Lessons from the Case Studies

The multifaceted groundwater challenges in the region have triggered many interventions that apply to a variety of settings. The following lessons come from the case studies as a group:

- The suitability and potential for success of an intervention in any given context rely on a complex mix of environmental, political, socio-economic and technical factors, which need to be understood.
- Community participation is a common element.
- Groundwater challenges and choices about responses do not occur in a vacuum. A wide range of public policy objectives can come into play and policy choices in one area can have unintended consequences for groundwater resources and vice versa.
- Community willingness to pay for improved water delivery in both urban and rural contexts has been demonstrated by several of the interventions.
- Apart from well-known and documented cases, new management interventions are emerging, such as innovations from the energy sector and novel forms of MAR that address multiple water challenges.
- Political will—driven by social, political, and economic environments—is a common thread in converting good ideas and experiments into policies and programs.
- No single intervention alone has achieved or can achieve sustainable use of groundwater resources. A mix of solutions is necessary.
- The evidence base behind the interventions is moderate, usually context specific, and often complicated by changing patterns of critical factors (for example, rainfall, water demand, and land use) even while a study is ongoing. This indicates a need for robust and long-term data on the outcomes of each intervention to better understand their scalability and transferability.
- Although many of the management options are investment ready for scaling up and transferring to other areas, such changes in scale are rarely straightforward. Both technical and institutional support are needed to achieve effective implementation.
Although showcasing a range of solutions to suit different contexts, these case studies as a whole represent creative attempts to improve the groundwater situation in the absence of effective groundwater governance (see chapter 4). This viewpoint does not dismiss the considerable financial and in-kind support provided by governments for many of these interventions; rather, it observes that they occur in the context of limited institutional capacity and regulatory interventions and in response to failures in governance.
Groundwater is a critical resource and a source of both opportunity and risk for people in South Asia. Groundwater provides a drought-secure resource for drinking water, agriculture, and industry, and about 1.5 billion people in the region depend on it for their daily water needs. As the region experiences climate and socioeconomic change, the future resilience of its population and ecosystems hinges on sustainable management of groundwater, where an already sizable proportion of the population is affected by its overexploitation. The depleted status of many groundwater systems in South Asia represents an increasing challenge to support current levels of use, even in a normal year. As depletion worsens, continued extraction from these systems is increasingly robbing supplies from future years and compromising their ability to maintain resilience in drought years. Affected areas are spread across the region, in arid and humid climates, urban and rural areas, and hard rock and alluvial aquifers. Groundwater dependence beyond replenishable limits and contamination beyond self-repair are major challenges requiring stakeholders with insight, vision, and collaboration power to identify and implement solutions.

Although recognition of the strategic importance of groundwater is increasing, the transition to proactive management is lagging. There is wide acceptance of the need to improve groundwater governance and strengthen drought resilience, but the lack of consistent and integrated groundwater-related policies leaves the region vulnerable to overuse and pollution.

The natural inertia in groundwater systems is reflected in the time taken for problems of overextraction and compromised quality to become evident. This same inertia means that management interventions will not necessarily show effects immediately; thus, they need to be supported and evaluated over extended periods. The pilots presented in this study show intervention techniques and adaptation willingness, but the benefits of efficiency, sustainability, and equity are not always clear. Each site is unique and may require trade-offs. Evidence is not yet strong enough to develop easily replicable blueprints for national or regional scale.

The intrinsic properties of aquifer systems means there are no cost-effective alternatives that could replace groundwater on such a large scale. Maintaining and expanding critical water supplies and ecosystem services will depend on groundwater governance to protect the quality of groundwater, enforce judicious use within long-term replenishment limits, and encourage conjunctive management of surface and groundwater resources, including unconventional resources like recycled wastewater.

No Silver Bullets

The case studies included in this report provide a flavor of the extent and applicability of management interventions that respond to challenges and help groundwater systems support drought-resilient communities. Although many of the examples provided are “investment ready” in that they could technically be adopted in similar settings throughout South Asia, there is limited evidence of transferability to other settings and of scalability. Benefits clearly come from combining more than one approach, and no intervention can be successful without a demand management component. Creating a portfolio of interventions for each setting is more likely to be successful. Using a phased, learning-by-doing approach to scaling,
supported by extensive observations and analysis, would help lead to wider implementation.

**Scale Matters**

The case studies show a variation in scale of groundwater management techniques, and some can be carried out at the community level. However, others are large-scale activities. For example, the conjunctive management of surface water and groundwater in major irrigation areas requires collaboration between institutional water managers reporting to multiple departments and among different user groups whose water consumption is driven by a variety of economic factors. The origin of many groundwater challenges in South Asia lie in agriculture and energy, and solutions need to involve these sectors as well as the affected communities.

**Stakeholder Participation Contributes to Many Objectives**

Many of the innovations profiled in the case studies relied on a social component. Participatory management, for example, was used to maintain infrastructure or to teach communities essential concepts such as demand management and the consequences of variable rainfall. Even when participatory management benefits are unclear, it contributes to other outcomes that build a community’s drought resilience, and it is essential in the absence of a regulatory environment.

**Don’t Forget about Groundwater Quality**

Groundwater-quality problems were not directly addressed through the case studies in this report. However, all efforts to manage groundwater must include an understanding of how to preserve or improve water quality to safeguard public health. Ignoring this will lead to a deteriorating quality that will increasingly impair the capacity of groundwater to support drought resilience and have an impact on human health.

**Make a Critical Assessment of Supporting Laws and Regulations**

Countries with effective water resource management, use laws and regulations as tools to support better groundwater management. South Asian legal frameworks to manage water resources (groundwater, most specifically) tend to be less comprehensive and more antiquated than in other regions. In some South Asian countries, this may require addressing fragmented or duplicated governance and historical instruments with unclear legal force. An assessment of water laws can identify and fill gaps for the first time.

**Strengthen Policies That Reduce Inequity**

Unsustainable groundwater use, unmanaged conjunctive use, or perverse groundwater-related policies can increase inequity among water users who compete for access to a common resource. For example, tubewell owners with the financial resources to dig deeper wells benefit themselves as groundwater levels decline but hurt other members of the community who rely on existing (shallower) wells.

**Build Institutional Capacity within Relevant Branches of Government**

In most South Asian countries, no single agency governs groundwater, and management is fragmented among several institutions. This results in an inability to monitor water conditions and adopt management strategies that go beyond technical solutions. Existing water institutions must do a better job of governing and managing groundwater on behalf of the public, which requires institutional capacity building and collaboration with all sectors to manage water demand.

**Adopt the “Nexus” Approach to Improving Governance**

Successful groundwater governance and climate change adaptation require a multisectoral approach to
integrate policy and decision making. The source of many water governance issues is in agriculture and energy sector actions, so harmonizing intersectoral policies and coordinating decision-making processes are important. Adjustments may include correcting energy policy distortions and adopting price incentives to encourage farmers to adopt drought-resilient and rainfed crops and water conservation practices.

Support the Acquisition of Regional and National Data Sets

More and better data is needed to effectively manage groundwater. The costs and logistics of collecting, curating, and publishing large data sets are usually supported by governments. The effort to create new ones, if supported by national research institutions, can build local capacity and international collaboration.

Build Regional Cooperation

This study noted large differences between countries in terms of availability of data sets, use of analytical methods, and knowledge and capacities for groundwater governance. Greater regional cooperation could reduce these disparities and share data acquisition costs and expertise in developing solutions to common challenges. The transboundary aquifers shared by two or more countries in the region offer a possible entry point for cooperation and shared benefits. Shared groundwater data sets, training opportunities, and management expertise would help build regional drought resilience.

Communicate Groundwater Beyond Traditional Stakeholders

The urgency of groundwater governance and management must be communicated to politicians, decision makers in government, and the private sector. Stakeholders will change their behaviors and mind-sets only after they realize the risks of continuing business as usual. Groundwater researchers need to develop ways to explain the benefits of water governance in clear, simple language for the broad range of stakeholders.

Invest in New Research for Development

The case studies create a knowledge base that can help South Asian groundwater managers identify and adopt interventions. More work is needed to develop documentation and training materials about the techniques. Additional research should be planned to independently monitor and assess interventions at these and other sites for longer time periods. Research is also required to develop, expand, and share evidence about new and emerging groundwater interventions.
References


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## Appendix A
### Case Studies Prepared for This Study

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<th>Author(s)</th>
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