INSTITUTE FOR TRANSFORMATIVE TECHNOLOGIES

TECHNOLOGY BREAKTHROUGHS FOR GLOBAL WATER SECURITY

A deep dive into South Asia

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A man walks beside a canal in Punjab state, India.

EXECUTIVE SUMMARY

Among the most vexing problems the world is facing today is water security: rainfall patterns are shifting, alternating between drought and flood; water tables are permanently dropping; and pollution in water bodies is worsening in many countries. The combined effect of climate change, population growth, economic development, urbanisation and poor regulation are making it very difficult to pinpoint root causes and solutions alike. These problems are particularly severe in the developing world, no more so than in South Asia which is home to virtually every major water-related problem. This study explores, in depth, the specific water security challenges facing South Asia, with the belief that the solutions can be extrapolated to other parts of the world.

The study describes 12 major water security challenges across a broad range of water quantity and quality issues. Several water quantity challenges are especially significant: In many river basins such as the Indus, Krishna, Kaveri, Penna, Vaigai, Sabarmati and Banas basins, surface water is fully utilised in normal years, and the basins are therefore "closed". In some regions, particularly peninsular India, hard rock geology places a hard limit on the rate that groundwater may be abstracted. In closed river basins and hard rock regions, growing water demand due to rapid economic and demographic change cannot be met by continually increasing water supply. The presence of rapidly growing cities in these regions make water quantity challenges particularly acute.

The most pressing water quality challenge is faecal contamination of water due to inadequate management of human waste. Discharge of untreated sewage into rivers is common in urban areas, and open defecation is common in rural India. Water contamination by faecal pathogens causes diarrhoea and other diseases, resulting in hundreds of thousands of deaths annually in South Asia, primarily among children. Other important water quality challenges include the presence of naturally-occurring arsenic and fluoride in groundwater that is widely used for rural water supply, and exposure to diverse waterborne toxins from industrial effluent and agricultural run-off.

Other challenges that are locally important include waterlogging and salinization of irrigated agricultural land, increased likelihood of flooding during intense storms, intrusion of salt water into fresh water aquifers in coastal areas, and long-term alteration of the Indus River flow due to glacial melting. In alluvial regions of the Indus-Ganges-Brahmaputra basins, there is great variation in groundwater use intensity causing very different challenges: Groundwater over-extraction in Punjab and Haryana is causing gradual lowering of the water table, while in eastern India, groundwater resources are abundant yet less utilised due to economic water scarcity caused by lack of means to access sustainable local water sources.

While the focus of this water security report is on technological solutions, we briefly discuss several important non-technology levers based on economics, geography and behavioural change. Those with highest potential impact include the implementation of economic incentives and appropriate water pricing, and better spatial planning of crops based on agro-climate and water availability.

We then comprehensively map the available and emerging technology levers to enhance water security in South Asia. We identify potential interventions that seek any of these three approaches to water security: reducing water demand by using less water to achieve the same ends, increasing water supply to provide more water that can be used, and integrating multiple aspects of the water system to improve overall efficiency of water use.

An important water security lever is found in increasing the efficiency of irrigation water use. Improved irrigation techniques are available, at decreasing and often negative cost, that could substantially reduce water withdrawals while increasing crop production. Particularly in water constrained areas such as closed river basins and hard rock regions, localised irrigation techniques such as sprinkler and drip irrigation are available for higher value crops, to increase yield and control and obtain the greatest output from the available water. Flood irrigation of cereal crops is the largest single use of water in South Asia, though much of the applied irrigation water infiltrates into the soil and is reused as groundwater.

In addition to direct water-based interventions in the agricultural sector, other interventions such as nutrient and pest management as well as the use of improved seeds and other agronomic practices are available to increase crop yields through more effective use of the available water resources. This is particularly relevant for rainfed farms with limited opportunities for irrigation development, which produce a significant share of South Asian crops.

Another important lever is improving the distribution efficiency of urban water supplies. Roughly 40-50% of the water sourced by South Asian water utilities typically goes unaccounted for, mainly due to physical losses from leakage, but also to apparent losses from theft. Intermittency of water supply is common, leading to water contamination as well as pipe degradation. If successfully implemented, modern management methods and technologies such as smart water metering could reduce urban water losses substantially, to provide more usable water for residents and greater economic sustainability for water utilities.

A major lever for water quality improvement is improved management of human waste, in both urban and rural areas. This must be addressed on two fronts: ensuring that all faecal-contaminated water is purified prior to its consumption, and expanding effective sanitation coverage to eliminate sources of contamination and improve overall health conditions. A range of waste management technologies are available, including centralised sewage treatment facilities for densely-populated urban areas, and on-site treatment techniques for rural areas.

Numerous other technology levers can play important roles in effectively increasing the supply of good quality water. Seawater desalination is a mature technology with little opportunity for breakthrough improvements, though costs will continue to decline modestly as a function of scale and system integration. Brackish water desalination offers more opportunities for significantly improving efficiency and cost.

Technologies are available to effectively remove arsenic from groundwater, though operational models must be improved to enable large-scale benefits. Water contamination by environmental toxins from industrial effluent and agricultural run-off is a growing, yet poorly understood, threat to human wellbeing in South Asia. Proactively avoiding such contaminants is more effective than removing them from water supplies after the fact.

Various methods are available to capture and store rainwater to overcome strong seasonality of precipitation in South Asia. Household-level rainwater harvesting and storage as well as large-scale surface water storage in reservoirs can be locally useful but are unlikely to offer definitive solutions. Managed aquifer recharging is promising in some regions, by diverting rainfall run-off into stored groundwater, but in closed river basins will merely redistribute water among users but will not increase total supply. Atmospheric water capture has limited potential as a scalable water security solution, due to several fundamental physical challenges.

Eliminating economic water scarcity will require broader socio-economic interventions, though appropriate technologies for low-cost well drilling and water pumping can make important contributions. Inter-basin water transfer will continue to play a role in water system development, but we caution against reliance on large-scale long-term water redistribution plans.

Sub-surface drainage is an essential, yet underappreciated, component of irrigation schemes. Regions facing waterlogging, such as the lower Indus basin, will need continued drainage interventions to avoid yield decline due to soil salinization. Surface water drainage is a growing challenge in urbanising environments, because of increasing precipitation intensity due to climate change, as well as decreasing rainwater infiltration due to expansion of the built environment.

The water security challenges facing South Asia are complex, involving issues of water quantity and water quality across a range of temporal and spatial scales. No single intervention can definitively solve water security problems in the region, but numerous actions can be taken on many fronts that collectively can significantly enhance water security.

Although South Asia faces serious constraints to accessing adequate amounts of high-quality water to meet growing demands, there are major opportunities for technology interventions that can eliminate some of the current inefficiencies of current water use. Numerous common-sense things must happen to improve the efficiency of water use in South Asia, by implementing current global best practices in multiple sectors, and broadly expanding the use of existing state-of-the-art knowledge.

In addition, we identify 5 new technology imperatives which, if successfully developed and deployed, will significantly enhance water security in South Asia:

1. Scalable sewage treatment systems with energy and water recovery
2. Gene-edited crops with higher tolerance to drought, heat and salinity stress
3. Network of distributed IoT sensors to measure and map water quality
4. Very low cost scalable technique for desalinating brackish water
5. Low-cost well drilling and pumping tools to expand groundwater access

Women in Odisha return home from work in the paddy fields.

1. INTRODUCTION

The Institute for Transformative Technologies was founded in 2015 to identify, develop and deploy technology solutions to the biggest social and environmental challenges affecting the global poor. To accomplish its mission, ITT partners with leading R&D institutions, NGOs, governmental and inter-governmental agencies, and established companies in developing countries with proven commitments to addressing social problems.

Recognising the fundamental importance of water to human wellbeing, ITT has adopted a strong focus on water security issues. Water security is a multi-faceted challenge involving physical water scarcity, economic water scarcity, and poor water quality. Exhibit 1 shows the estimated percentage of the global population facing each of three types of water problems: physical scarcity, economic scarcity, and poor quality.

This is based on ITT's analysis combining definitions and data from multiple sources.[1] We categorize a country as facing a water quality problem if the death and disease due to water-related diarrhoeal diseases exceed a threshold.[2] We categorize a country as facing physical water scarcity using WRI's rating of water stress by country based on ratios of total withdrawals to total renewable supply (WRI 2013).[3] We base economic water scarcity on the mapping done by (WWAP 2012) supplemented by country-specific analysis.

While this broad-brush national-level analysis lacks many nuances of local water security, it gives strong directional indication of the types and scales of global water security problems. Further details of the specific water security challenges in the ten largest countries are provided in Table 1.

[1] Based on the 50 largest countries by population (year 2018 projection by UN 2017), which collectively are home to 87% of the global population.
[2] Countries are considered to have water quality problems if the annual disability-adjusted life years (DALYs) lost to water-related diarrhoeal diseases exceed 500 per 100,000 people, based on 2015 DALY data (Troeger et al. 2017) and 2015 population data (UN 2017). DALYs are an indication of the severity of a disease's impacts on a population including morbidity and mortality effects.
[3] Countries are considered to have physical water scarcity if they have "medium to high" or greater average exposure of water users to water stress, based on ratios of total withdrawals to total renewable supply.

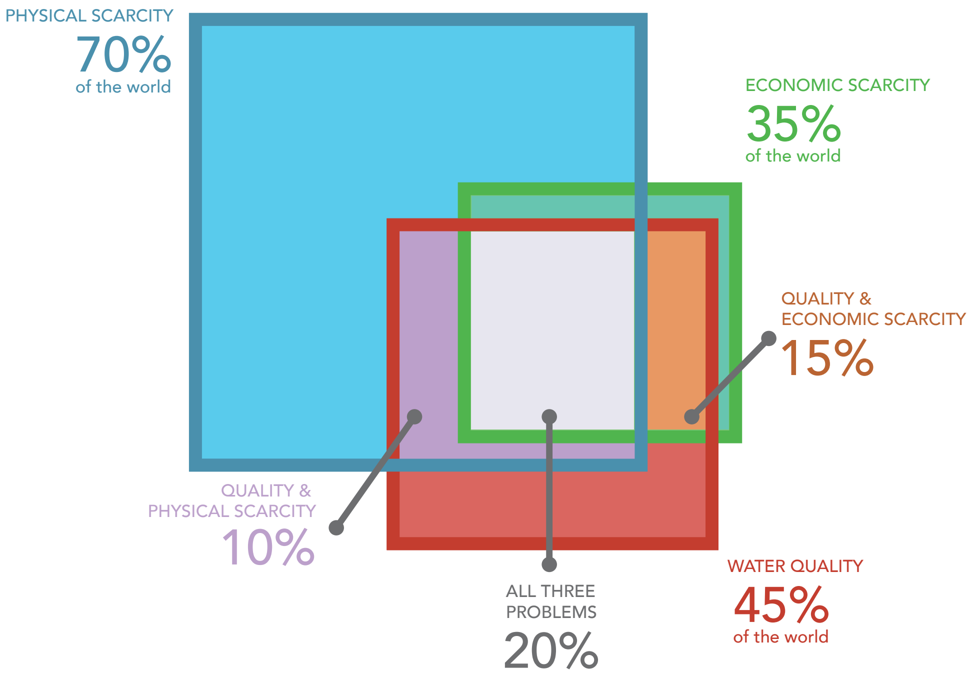

Exhibit 1. The world's 'water problem' can be characterized as the intersection of three problems— physical scarcity (i.e., where consumed water is a major share of all renewably available water), economic scarcity (where water is present but cannot be accessed due to lack of economic means), and quality (due to contamination of water by biological or chemical impurities). Different countries face different combinations of these problems, based on their geography, population, level of industrialisation, economic activity and management practices. According to our analysis 85% of people live in countries that face at least 1 of these 3 problems; 45% live in countries facing at least 2 of the 3 challenges, and 20% face all 3 problems at the same time. (Source: ITT analysis)

Based on these definitions, only 15% of the world's population lives in countries without major water-related problems; these countries include Brazil, Russia and Germany.[4] The remaining 85% of the world's population live in countries that face at least 1 of the 3 problems.

- Sub-Saharan Africa and South Asia primarily bear the brunt of economic water scarcity. These regions are also dominated by agriculture and smallholder farming.
- 20% of the world's population live in countries facing all 3 problems simultaneously, primarily people living in India.
- 15% of the world's population live in countries facing poor water quality and economic water scarcity, including the countries of Bangladesh, Nigeria and Ethiopia.
- 40% of the total population live in countries primarily facing physical scarcity of water, including the countries of China, USA and Mexico.
- 10% of total population suffers from poor water quality and physical scarcity/ unsustainable use, in countries including Indonesia, Pakistan and South Africa.

[4] The coarseness of this national-scale analysis is evident, e.g. Brazil overall is very water abundant, though cities like São Paulo have faced severe deficit; Russia overall has low diarrhoeal rates, but some locations suffer from severe industrial water contamination.

- A very small number of countries face the challenges of quality or economic scarcity, in exclusion of the other problems.

Legend: Severe | High | Moderate | Fair | Low

	China	India	USA	Indonesia	Brazil	Nigeria	Pakistan	Bangladesh	Russia	Mexico
Surface water supply in closed river basins is fully utilsed and cannot increase	Severe	Severe	High	Low	Fair	Fair	Severe	Low	Low	Moderate
Groundwater over-extraction in hard rock regions causes seasonal critical depletion	High	Severe	Fair	Fair	Low	Low	Moderate	Fair	Low	Moderate
Groundwater over-extraction in alluvial regions causes long-term decline of water table	Severe	Severe	Severe	Low	Low	Low	Severe	Low	Low	High
Faecal contamination of water bodies causes health and environmental impacts	Low	Severe	Low	Moderate	Fair	Severe	Severe	Moderate	Low	Fair
Arsenic and fluoride contamination of groundwater causes health impacts	Moderate	High	Fair	Low	Low	Low	Moderate	Severe	Low	Fair
Diverse industrial effluent and agricultural runoff cause health and environmental impacts	Severe	High	Fair	Low	Fair	Fair	Moderate	Fair	Moderate	Moderate
Urban water demand from growing cities exceeds local supplies	Severe	Severe	Severe	Fair	High	Moderate	Severe	Fair	Low	Severe
Available water supply becomes brackish or saline from groundwater salinization	Moderate	Moderate	Fair	Fair	Fair	Fair	Moderate	High	Low	Fair
Irrigated agricultural land becomes waterlogged and salinized over time	Moderate	Moderate	Moderate	Low	Low	Low	Severe	Low	Fair	Fair
Flooding during storms will become more frequent and intense	Moderate	Moderate	Moderate	Fair	Fair	Fair	Moderate	Moderate	Low	Fair
Glacial melting is permanently altering surface water flow	Fair	Fair	Low	Low	Low	Low	High	Fair	Low	Low
Lack of means to access local water sources causes economic water scarcity	Fair	High	Low	Moderate	Fair	Severe	Moderate	High	Low	Fair

Table 1. People around the world face a diverse set of water problems of varying severity. Here, the severity of 12 major water security challenges is estimated for the 10 largest countries by population. The 12 challenges are described in detail in Chapter 3. (Source: ITT analysis)

With this global perspective in mind, we chose to focus this report on the specific region of South Asia, which faces a diverse set of water security issues that are unparalleled in scale. We base our mapping of water-sector technological levers on the specific range of water security challenges in the South Asian region. Nevertheless, the conclusions of this analysis extend globally to other regions that face similar types of problems. The goal of this report is to focus the attention of policymakers, investors, entrepreneurs, scientists and engineers toward the potential technologies that are most capable of solving the water security challenges in South Asia and globally.

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Not all reviewers may agree with our findings, and any errors are the full responsibility of the authors.

The Jhelum River is a tributary of the Indus River and runs through eastern Pakistan into northwestern India.

2. TIMELINE OF WATER SECURITY MILESTONES IN SOUTH ASIA

100 million years ago - 60,000 years ago

100 million years ago: Tectonic plate that would become peninsular India breaks off from Pangea supercontinent. Natural processes of weathering, erosion, sedimentation and ecology shape the surface of the landmass

50 million years ago: The Indian tectonic plate, moving northwards at the speed of ~20 cm per year, begins to collide with the Eurasian tectonic plate that is moving northwards more slowly

50 million years ago - present: Uplift of Himalayan mountain range, and erosion of sediments to form the Indus, Ganges and Brahmaputra river basins (see Exhibit 2)

40 million years ago - present: Regional climate is shaped by the Himalayan range, which intercepts atmospheric moisture, sending it southward in South Asian rivers, leaving the Tibetan plateau arid

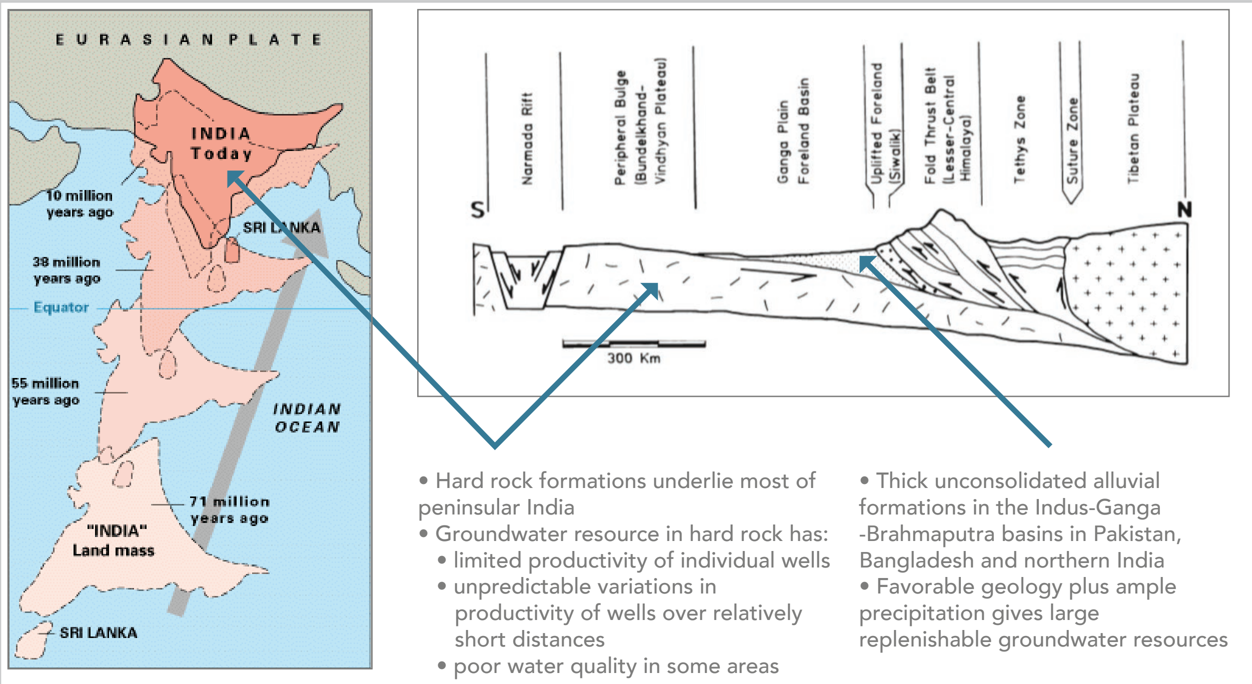

Exhibit 2. Water security in South Asia is strongly influenced by the geologic origins of the regions. The Indian tectonic plate is slowly colliding with the Eurasian plate, forming the Himalayan mountain range. Eroded sediment from that range has formed the basins of the Indus, Ganges and Brahmaputra river systems. (Source: images from USGS 2007, Singh 1996)

60,000 BCE - 1800 CE

60,000 BCE: Modern humans migrate to South Asia, living by gathering and hunting

9000 BCE: Development of rainfed agriculture based on domestication of crops and animals

4500 BCE: Irrigation techniques are developed by the Indus Valley Civilisation

3000 BCE: Reservoirs are constructed at Girnar (Gujarat) to store rainwater

2200 BCE: Sanitation facilities are introduced in South Asia in urban areas of the Indus Valley Civilisation

200 CE: Kallanai Dam (also known as Grand Anicut) across the Kaveri River is built

1335 CE: Western Yamuna Canal is built, but ceases to flow by 1750 due to siltation

1500s CE: Public shared toilets are constructed during Mughal era

1600 CE: Large run-of-river schemes and inundation canals are constructed by the Mughals

1800 CE - 1960 CE

1800 CE: About 800,000 hectares of farmland are irrigated in South Asia

1817 to 1923 CE: Six separate cholera pandemics each originate in the Ganges River delta near Kolkata (eastern India) and spread throughout the world

1863 CE: The Royal Commission of the British army in India reports on the unsanitary conditions of the army and recommends the creation of a Commission of Public Health to improve sanitation and prevent epidemics among the soldiers

1864 CE: Sanitary Commissioners and corresponding boards are appointed in each province of British India

1890 CE: British India leads the world in irrigated land area, with 12 million hectares (followed by USA with 3 million ha, Egypt with 2 million ha, Italy with 1.5 million ha)

1917 CE: Punjab Drainage Commission is formed to address the increasing problem of waterlogged soil (see Exhibit 3)

1947 CE: About 22 million hectares are irrigated in South Asia (see Exhibit 4)

1954 CE: Government of India implements the first of several river conservation programs that focus on reducing the amount of wastewater entering rivers by allocating funds to build sewage treatment plants

1950-60s CE: Salinization increasingly affecting farmland in Sindh Province in Pakistan

1960 CE: Indus Waters Treaty is signed by Pakistan and India, giving India control over the three "eastern" rivers (the Beas, Ravi and Sutlej), and Pakistan control over the three "western" rivers (the Indus, Chenab and Jhelum)

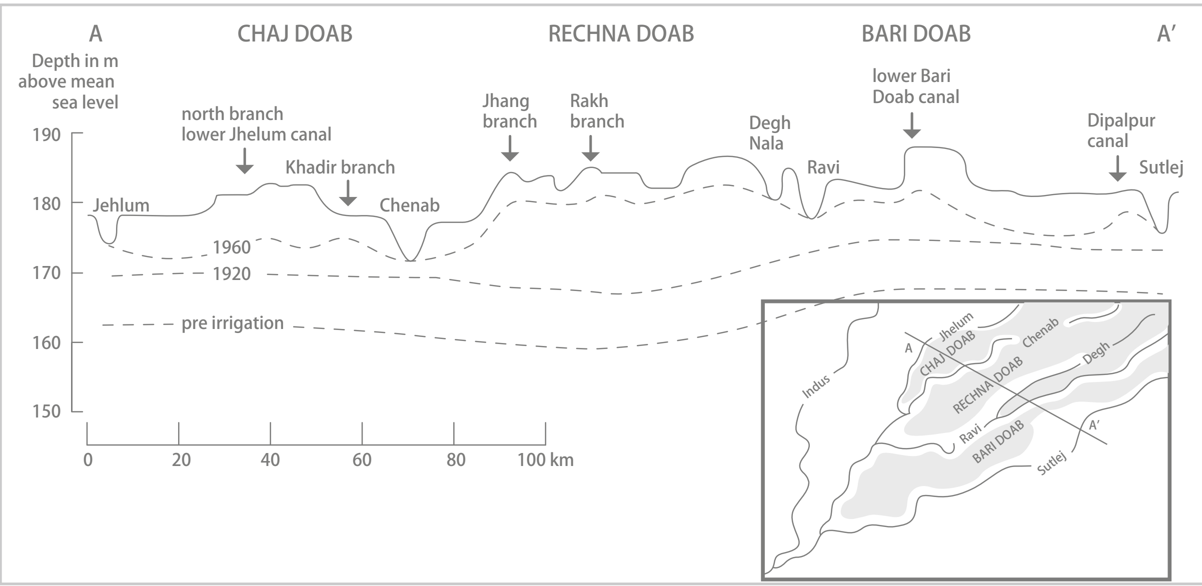

Exhibit 3. Groundwater level has risen since the introduction of canal irrigation in Punjab, due to canal leakage and irrigation water infiltration. (Source: Bhutta & Smedema 2007)

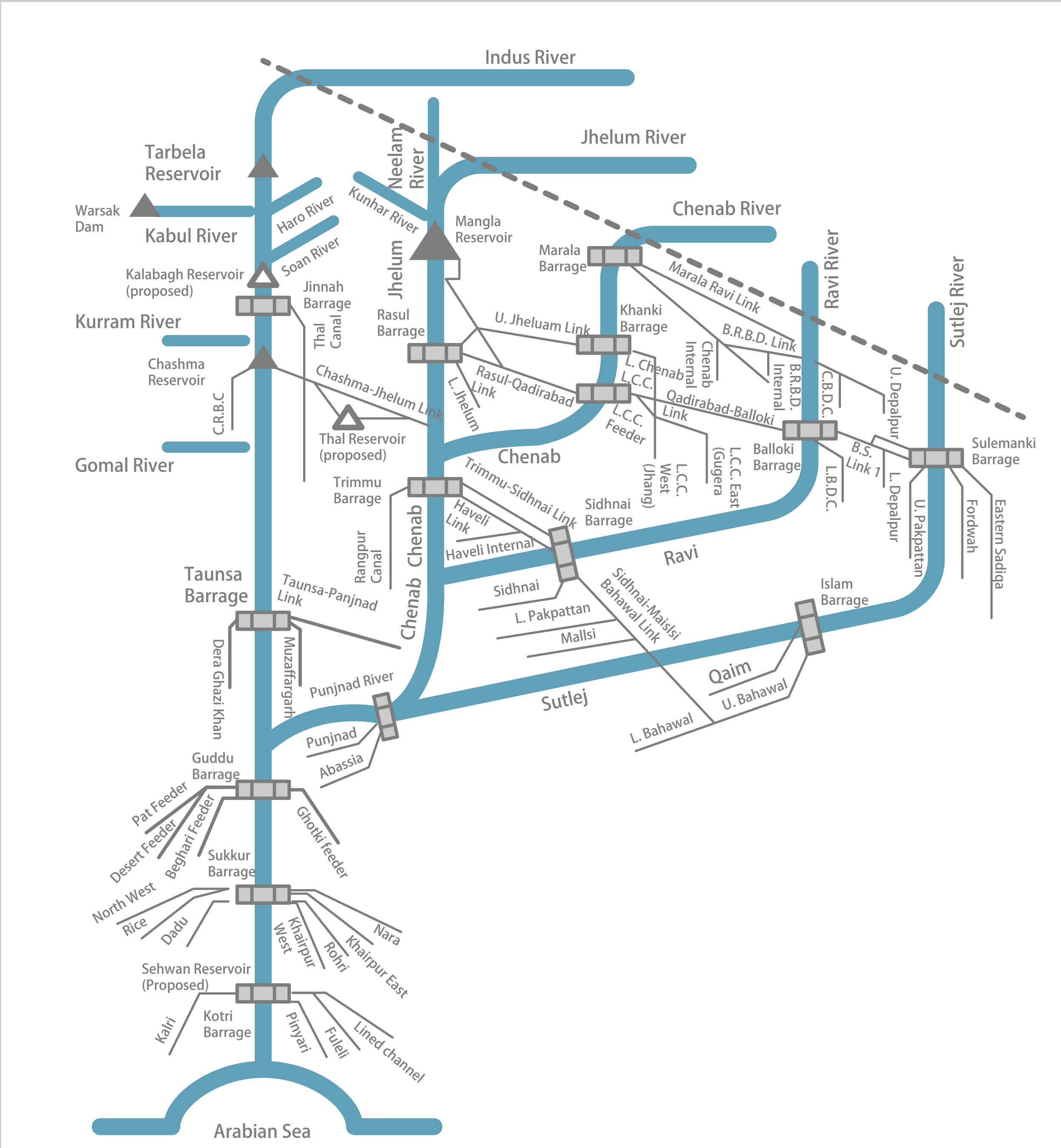

Exhibit 4. The Indus Basin Irrigation System (IBIS) is the largest contiguous irrigation system in the world, providing water to about 15 million ha of farm land in Pakistan. (Source: World Bank 2005b)

1960 CE - present

1963 CE: Indian Prime Minister Nehru describes the Bhakra Nangal dam project as "the new temple of resurgent India"

1965: India imports seeds of high-yielding wheat varieties from Mexico

1970s CE: The number of borewells begins to increase sharply, for irrigation and domestic water supply (see Exhibit 5)

An Indian tubewell.

1970s-1990: Major subsurface drainage projects implemented in Pakistan to mitigate waterlogging (SCARP: Salinity Control and Reclamation Project)

1970s-1990s: Exposure to arsenic and fluoride increases, as borewell water replaces surface water for domestic consumption

1970s-present: Fertiliser consumption increases sharply, as part of agricultural intensification

late 1970s-early 1980s: Introduction of flat electricity tariffs for irrigation pumping, in place of metered tariffs

1980s-present: Cropping patterns shift to more water-intensive crops such as rice and sugarcane

1992: Solar-powered water pumping programme started by India's Ministry of New and Renewable Energy

1990s-present: Per capita consumption of water-intensive products rises with affluence (see Exhibit 6)

2000: Arsenic contamination of drinking water in Bangladesh is described as "the largest mass poisoning of a population in history"

2015: Most households in South Asia have access to improved drinking water sources, but a significant number of people (4 million in Bangladesh, 22 million in Pakistan, and 163 million in India) continue to rely on unimproved sources (see Exhibit 7)

2017: About 92 million hectares of farmland are irrigated in South Asia

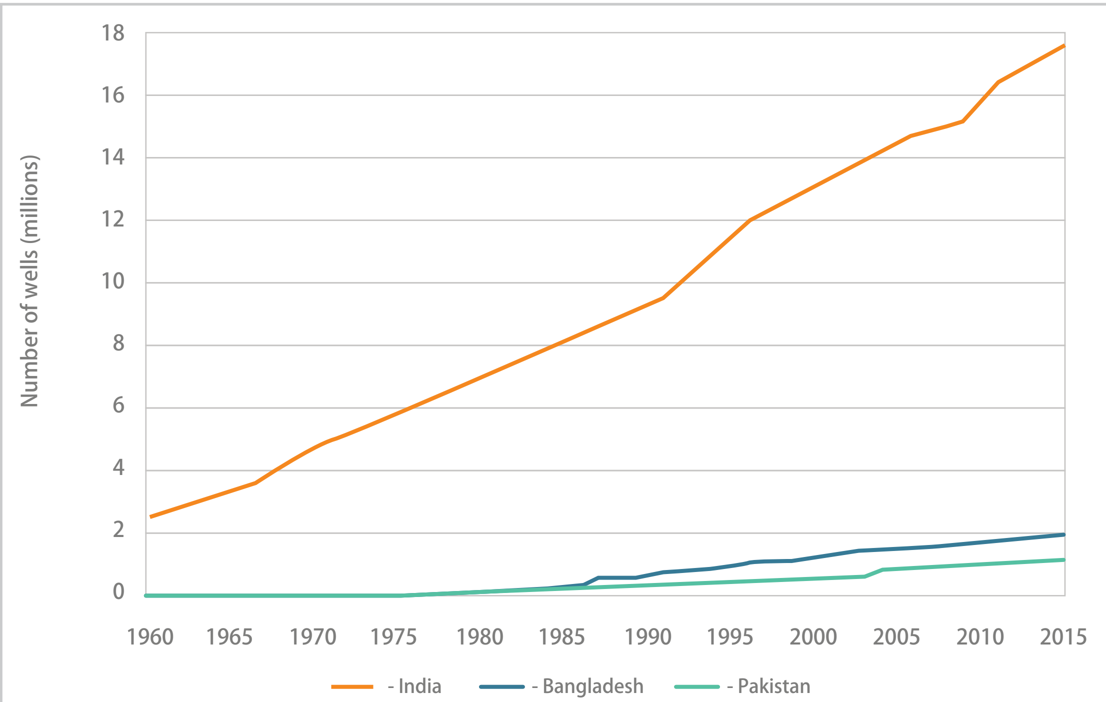

Exhibit 5. The number of wells in South Asia has increased rapidly in recent decades, as demand for groundwater has grown (Source: ITT analysis based on data from World Bank 2005a, Qureshi et al. 2010, World Bank 2010, Shankar et al. 2011, Shamsudduha 2013, Siddiqi & Wescoat 2013, Rawat & Mukheri 2014, Suhag 2016)

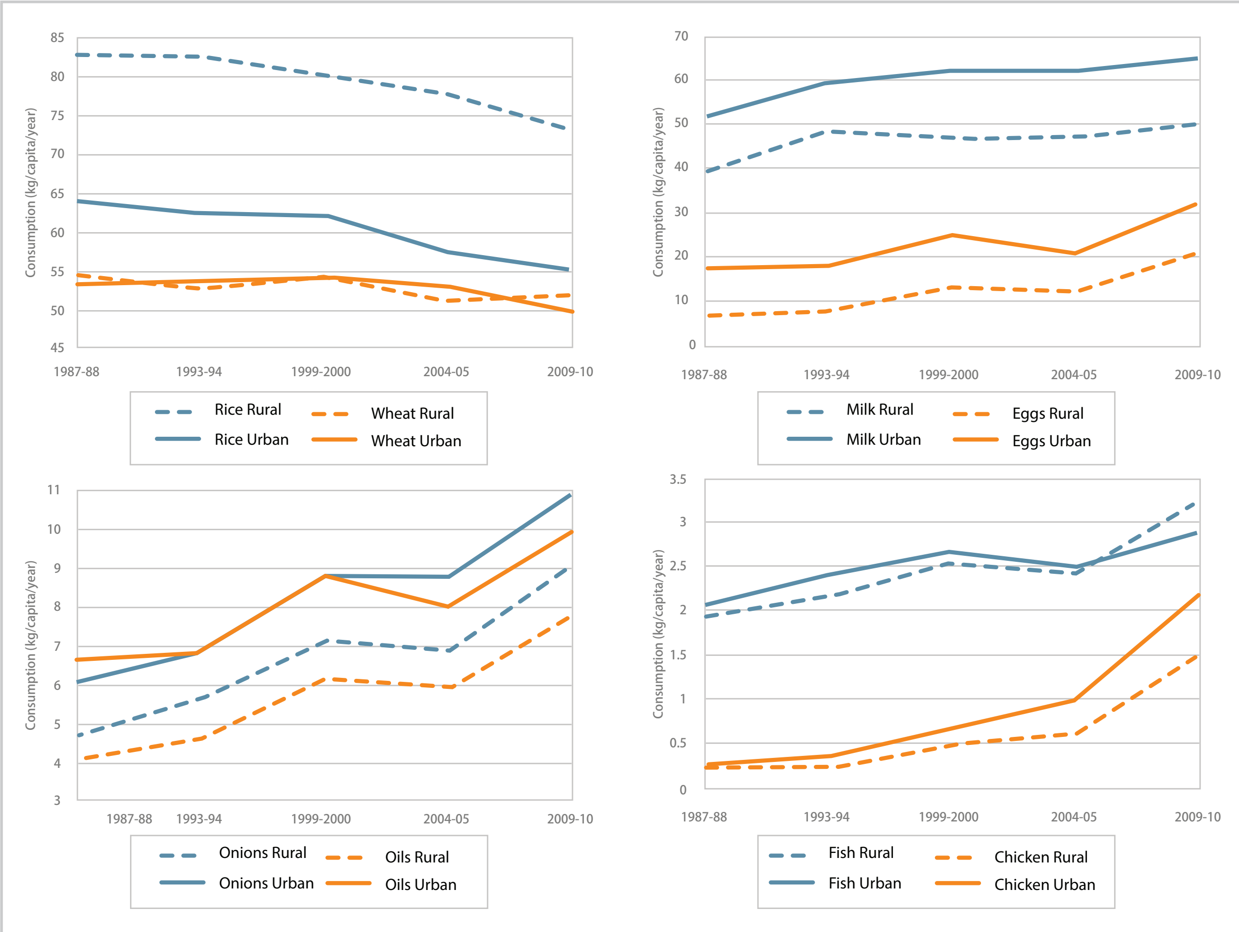

Exhibit 6. Per capita consumption in South Asia is increasing for many food products including milk, eggs, vegetables, oils, fish and chicken. Per capita consumption of rice and wheat is decreasing. Solid and dashed lines show trends in urban and rural areas of India, respectively. (Source: data from NCAER 2014)

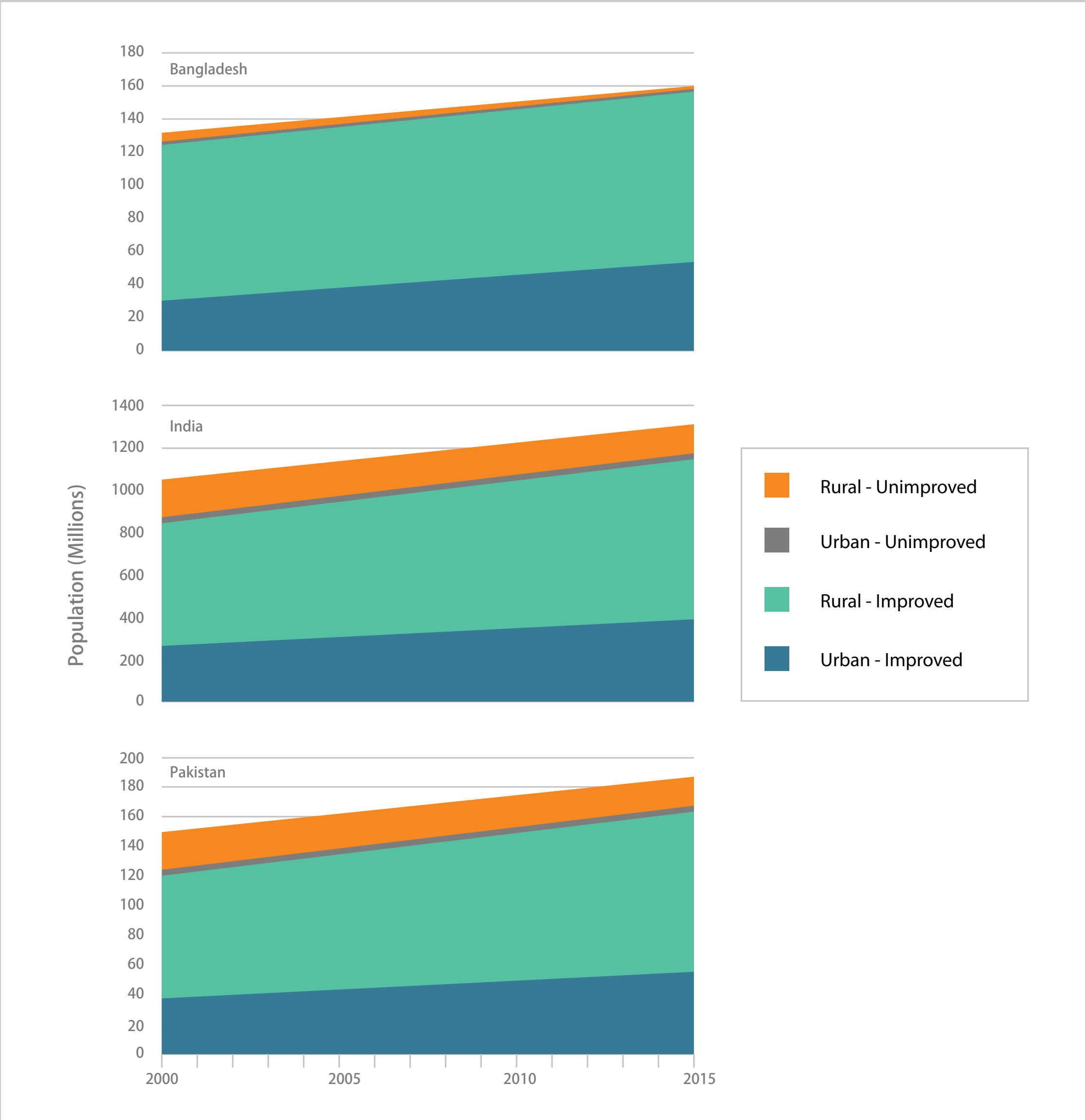

Exhibit 7. The number of people in South Asia with access to improved sources of household water is increasing in both urban and rural areas. There remains, however, a significant share of the population that does not have access to improved water sources. (Source: data from JMP 2017[5])

[5]Access to household water includes aspects of water availability, quality, and delivery. The WHO/UNICEF Joint Monitoring Program (JMP) has developed "service ladders" to categorize household water services around the world in an effort to monitor and improve access. According to the JMP, "Improved household water sources are those that have the potential to deliver safe water by nature of their design and construction, and include: piped water, boreholes or tubewells, protected dug wells, protected springs, rainwater, and packaged or delivered water." Categories include Safely Managed, Basic, Limited, Unimproved, and Surface Water. The table below briefly defines each category. In the figures, "Improved" access includes Basic and Safely managed categories, and "Unimproved" access includes Limited, Unimproved, and Surface Water categories.

Category	WHO/UNICEF JMP Definition
Safety Managed	Household water from an improved water source which is located on premises, available when needed and free from faecal and priority chemical contamination
Basic	Household water from an improved source, provided collection time is not more than 30 minutes for a roundtrip including queuing
Limited	Household water from an improved source for which collection time exceeds 30 minutes for a roundtrip including queuing
Unimproved	Household water from an unprotected dug well or unprotected spring
Surface Water	Household water directly from a river, dam, lake, pond, stream, canal or irrigation canal

Present - 2100 CE (projections)

2045 CE: Half of the population of South Asia lives in cities (see Exhibit 8)

Present-2100 CE: Global climate change continues to increase temperature, precipitation and variability in South Asia (see Exhibit 9)

2060 CE: Human population in South Asia reaches a peak, and then gradually declines (see Exhibit 10)

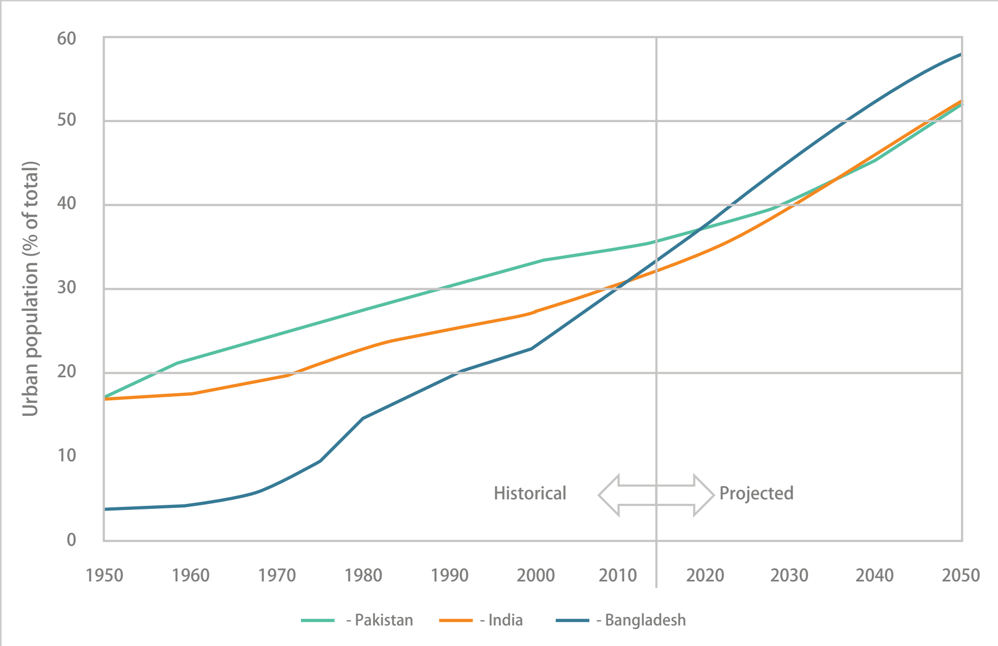

Exhibit 8. The proportion of population living in urban areas is increasing in South Asia. Currently about one third of the region's population lives in cities. (Source: data from UN 2018)

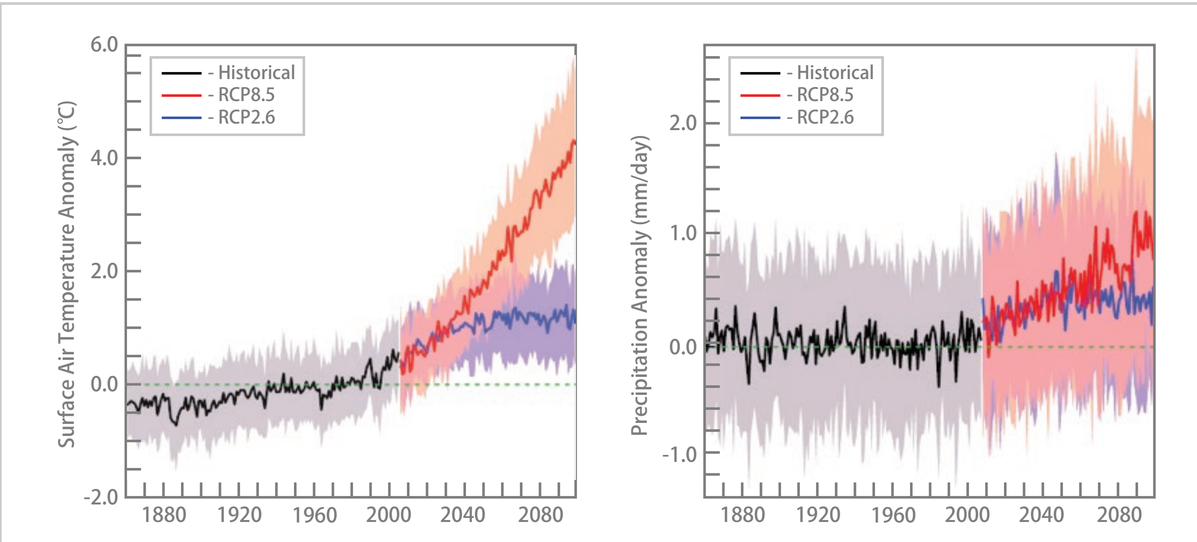

Exhibit 9. Air temperature and total precipitation are projected to increase in South Asia through 2100. The magnitude of the increases will depend on future greenhouse gas emission trajectories. The figure shows temperature and precipitation projections for India: red lines represent the high-emission RCP8.5 scenario, blue lines represent the low-emission RCP2.6 scenario. (Source: Jayasankar et al. 2015)

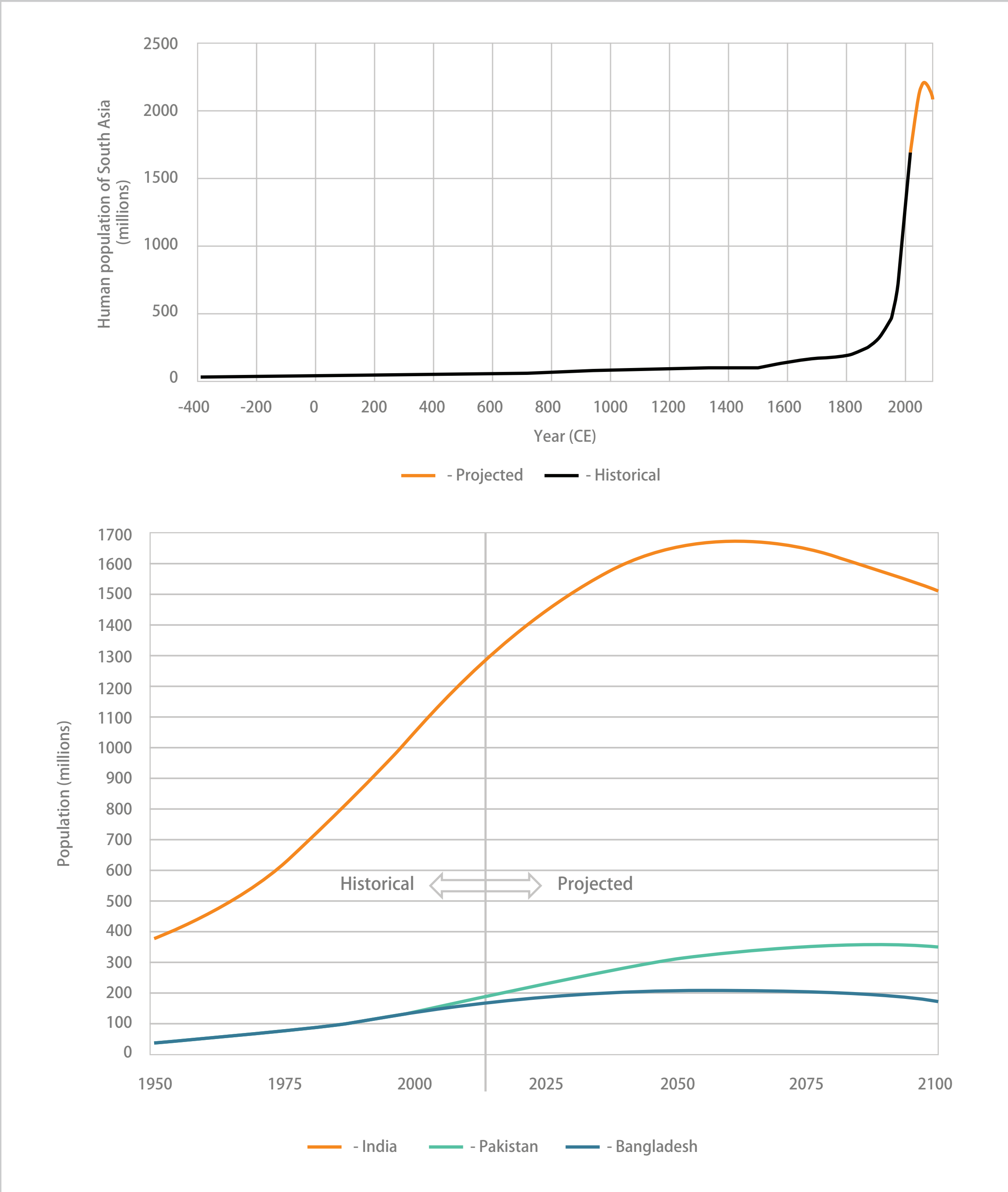

Exhibit 10. The human population of South Asia expanded gradually for two millennia, and then expanded very rapidly during the past century. Population is projected to continue growing for several more decades, and then begin to decrease during the second half of the 21st century. (Source: population prior to 1950 from McEvedy & Jones 1978; population from 1950 to present from UN 2017; future projection from UN 2017 medium fertility variant[6])

[6]In 2017, Pakistan conducted its first population census since 1998 (Pakistan Bureau of Statistics 2017). The census indicated a total population of 207.8 million, or 5.5% greater than the 2017 population shown here as estimated by the UN (2017). Therefore, due to both the higher current population and the higher actual fertility rate, the projection shown here underestimates the expected future population growth of Pakistan.

Stagnant pollution in Chennai.

3. WATER SECURITY CHALLENGES IN SOUTH ASIA

South Asia faces numerous water security challenges now and in the coming decades. Some areas face only one challenge, some face several, but no area of South Asia is free from any water security challenge. The following sections outline the key water security challenges in South Asia.

3.1 Surface water supply in closed river basins is fully utilised and cannot increase

A river basin is considered "closed" when all of the surface water available in an average year is fully allocated, and little or no river water discharges into the ocean (Molle et al. 2010). Several major river basins in South Asia are now closed basins, including the Indus in Pakistan, the Krishna, Kaveri, Penna and Vaigai in southern India, and the Sabarmati and Banas in western India (World Bank 2005b, Venot et al. 2007, Kumar et al. 2008, Falkenmark & Molden 2008).

In these basins, the total annually available surface water supply is fully or nearly fully utilised. There is little or no opportunity to increase extraction of surface water in these regions to meet rising urban and agricultural demands (Venot et al. 2007).

The Indus River basin, for example, is extensively developed to use surface water in the largest contiguous irrigation system in the world, the Indus Basin Irrigation System (IBIS) (see Exhibit 4). Comprising three major storage reservoirs, 19 barrages, 12 inter-river link canals, and 45 major canal commands irrigating about 15 million hectares, IBIS uses virtually all the water flowing in the Indus River (see Exhibit 11, 12). The Krishna River basin in peninsular India is similarly developed to capture and use almost all available surface water (see Exhibit 13).

In closed basins, while river water is fully used during normal and dryer-than-normal years, some flood water typically reaches the ocean during years of above-average precipitation. Attempting to capture and utilise this "lost" water leads to diminishing returns, requiring significant infrastructure that will only be used irregularly, making 100% utilisation of river flow impractical.

During years of less-than-average precipitation the surface water supply will not meet demand in closed basins. Such years are projected to become more frequent due to climate change. In the absence of a structured water allocation system, upstream water users will continue to extract river water, while downstream users will be left with inadequate supply.

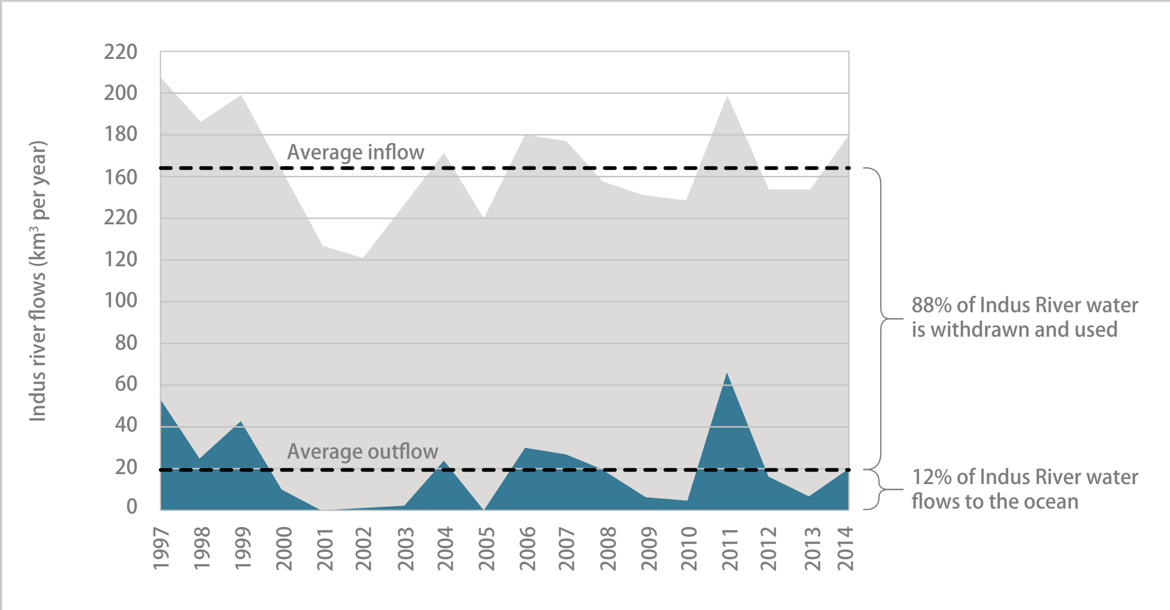

Exhibit 11. The Indus River basin is effectively "closed", with little opportunity to increase surface water extractions. Most of the river water available in an average year is already allocated and used. No water flows from the Indus River to the ocean in years of below-average rainfall. (Source: ITT analysis based on data from Pakistan Bureau of Statistics 2007, 2014; River inflow includes the Indus at Kalabagh, Chenab at Marala, Jhelum at Mangla, and minor inflows from Ravi and Sutleg Rivers; River outflow is discharge below Kotri barrage)

Exhibit 12. Kotri barrage in Sindh Province, Pakistan, is the last stop on the Indus River before it reaches the Arabian Sea. During years of normal precipitation, little water flows in the Indus River below Kotri Barrage. (Source: Google Maps 2018)

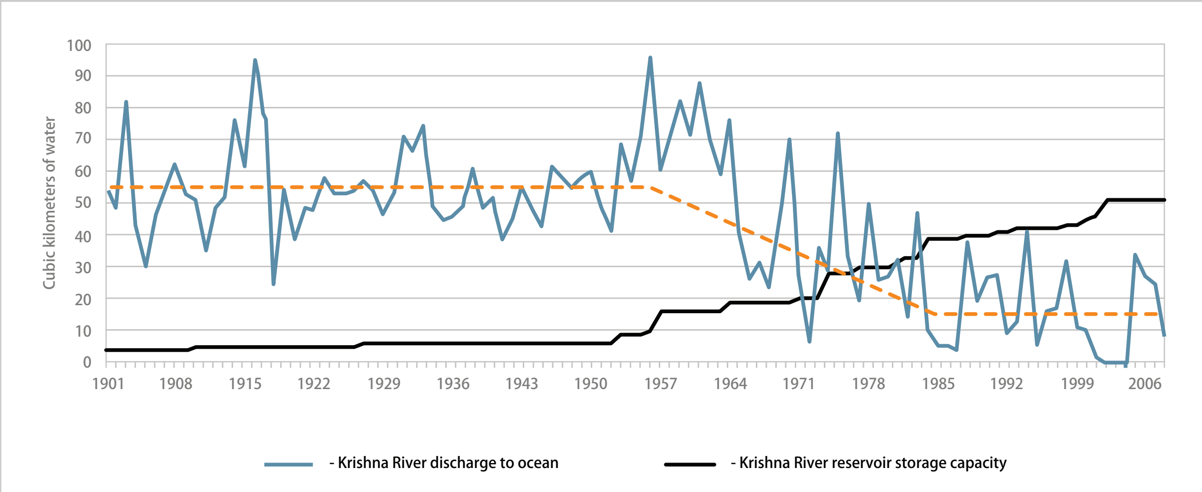

Exhibit 13. The Krishna River basin is reaching closure. While average rainfall in the basins has remained steady over the long term, average discharge to the ocean has decreased to near zero. An increase in reservoir storage capacity has enabled the capture and utilisation of most surface water in the basin. Between 1901 and 1956, an average of 55 km^3 of discharge water flowed to the ocean each year; between 1984 and 2008, the average annual discharge was only 15 km^3. (Source: data from Venot et al. 2007; Biggs et al. 2008; Rao et al. 2010)

Among the various uses of freshwater, environmental flows are those required to sustain riverine and estuarine ecosystems and to maintain other natural river processes. In best-practice resource management, a sufficient amount of river water is allotted to environmental flows, just as water is allotted to agriculture, industry, and communities. Environmental flow requirements are complex and varied, involving quantity, quality and timing of the water flows. Comprehensively defining and maintaining the required environmental flows is challenging in South Asia, due to the high hydrological variability, the difficulty and expense of waste treatment scale-up, water resource disputes between states/provinces, and a lack of quantitative data on relationships between river flows and river ecology (Smakhtin and Anputhas 2008).

As river basins approach closure, maintaining adequate environmental flows becomes more difficult since they reduce the amount of water available for other potential uses. Ensuring adequate environmental flows in rivers has not been a high priority in South Asia. Generally, little respect has been paid to the natural ecology of river basins and the biological, chemical and physical interactions within the watersheds (Smakhtin and Anputhas 2008).

In Pakistan, environmental flow requirements of the Indus River are not met during 11 months of the year, while the Ganges River in India faces environmental flow deficits during 8 months of the year (Jägermeyr et al. 2017). Pakistan's environmental flow deficits make up 31% of modelled global deficits, while India's make up 18% (Jägermeyr et al. 2017). These deficits are largely due to surface water withdrawals for irrigation.

3.2 Groundwater over-extraction in hard rock regions causes seasonal critical depletion

Groundwater has long been harnessed by the people of South Asia, using traditional technologies to create wells and extract water. Groundwater use increased rapidly in South Asia after the 1960s, as a key component of Green Revolution agriculture, based on boreholes and motorised pumps. Groundwater is now a major source of water in the region for agriculture, households and industry. In locations where high-quality groundwater is abundant, wells and boreholes can provide more flexible and reliable water supply, compared to surface water supply.

Groundwater occurs in porous underground formations, or aquifers, that are naturally recharged over time by rainwater infiltrating into the ground. Some aquifers are very porous and extensive, and other aquifers are less porous and of limited extent. Groundwater recharge depends on the timing and amount of precipitation, and on land surface characteristics and subsurface geology. Groundwater is removed from aquifers both by natural drainage, and by extraction from wells and boreholes. When the rate of removal exceeds the rate of recharge, the level of groundwater (the "water table") declines (see Exhibit 14).

Due to unique geologic origins of the South Asian landmass (described in Exhibit 2), there are two distinct groundwater regimes in South Asia: hard rock and alluvial.[7] Within India this distinction is clearly seen in Exhibits 15 and 16. In this section we discuss issues regarding groundwater depletion in hard rock regions; alluvial depletion is discussed in Section 3.3.

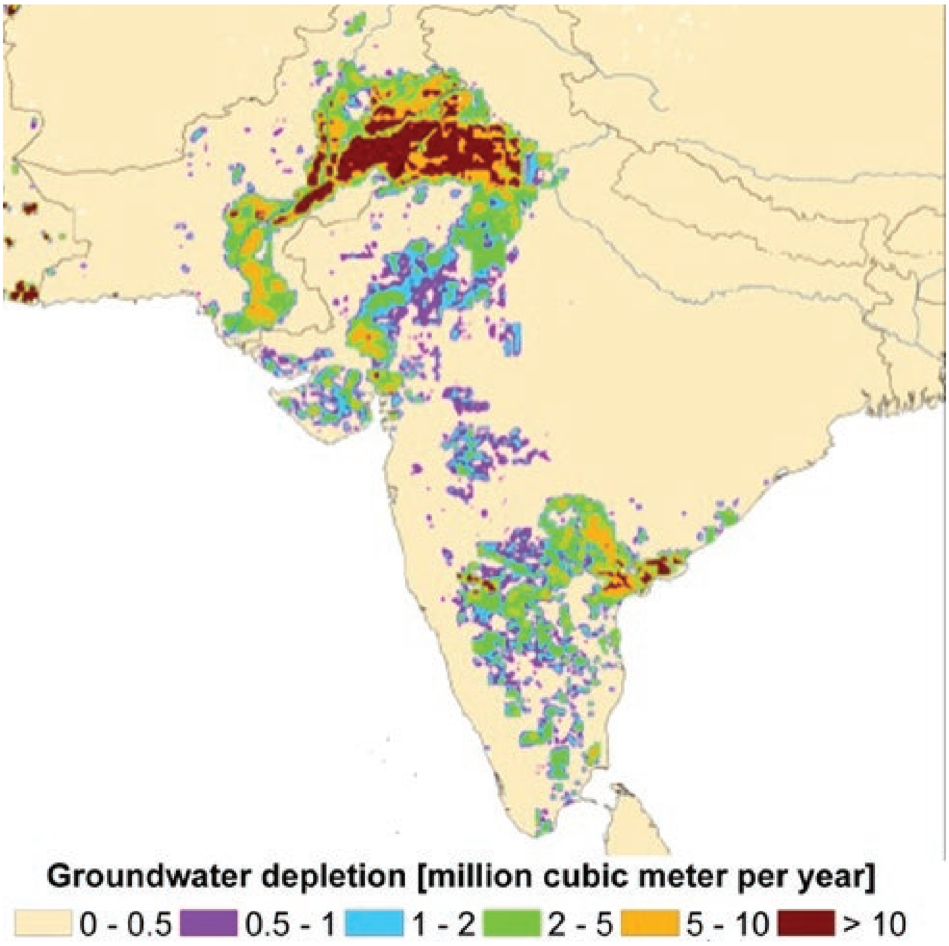

Exhibit 14. When abstraction of groundwater is greater than its replenishment, depletion of stock occurs. Current estimated groundwater depletion rate in South Asia is here shown in units of million cubic meters per year per grid cell (grid cells are 0.1° by 0.1°, or ~10 km by ~10 km at the equator). (Source: Wada et al. 2016)

[7]There are also semi-consolidated formations in South Asia, especially sedimentary formations, which are relatively minor in extent and importance, compared to hard rock and alluvial formations.

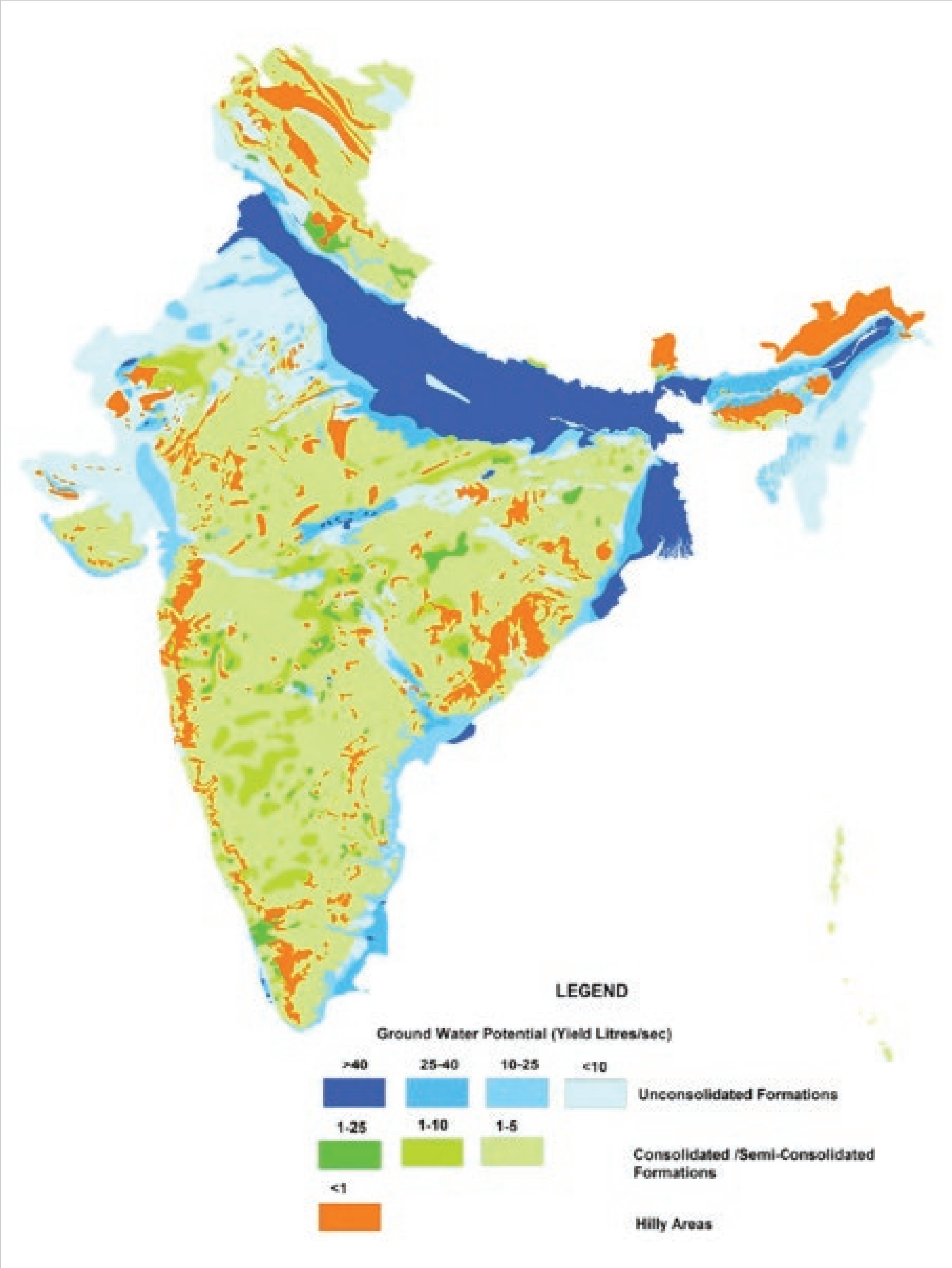

Exhibit 15. The hydrogeological conditions of India vary between regions. Unconsolidated alluvial aquifers in the Indo-Gangetic plain have large groundwater potential. Consolidated hard rock geology in peninsular India has much lower groundwater potential (Source: CGWB 2015a)

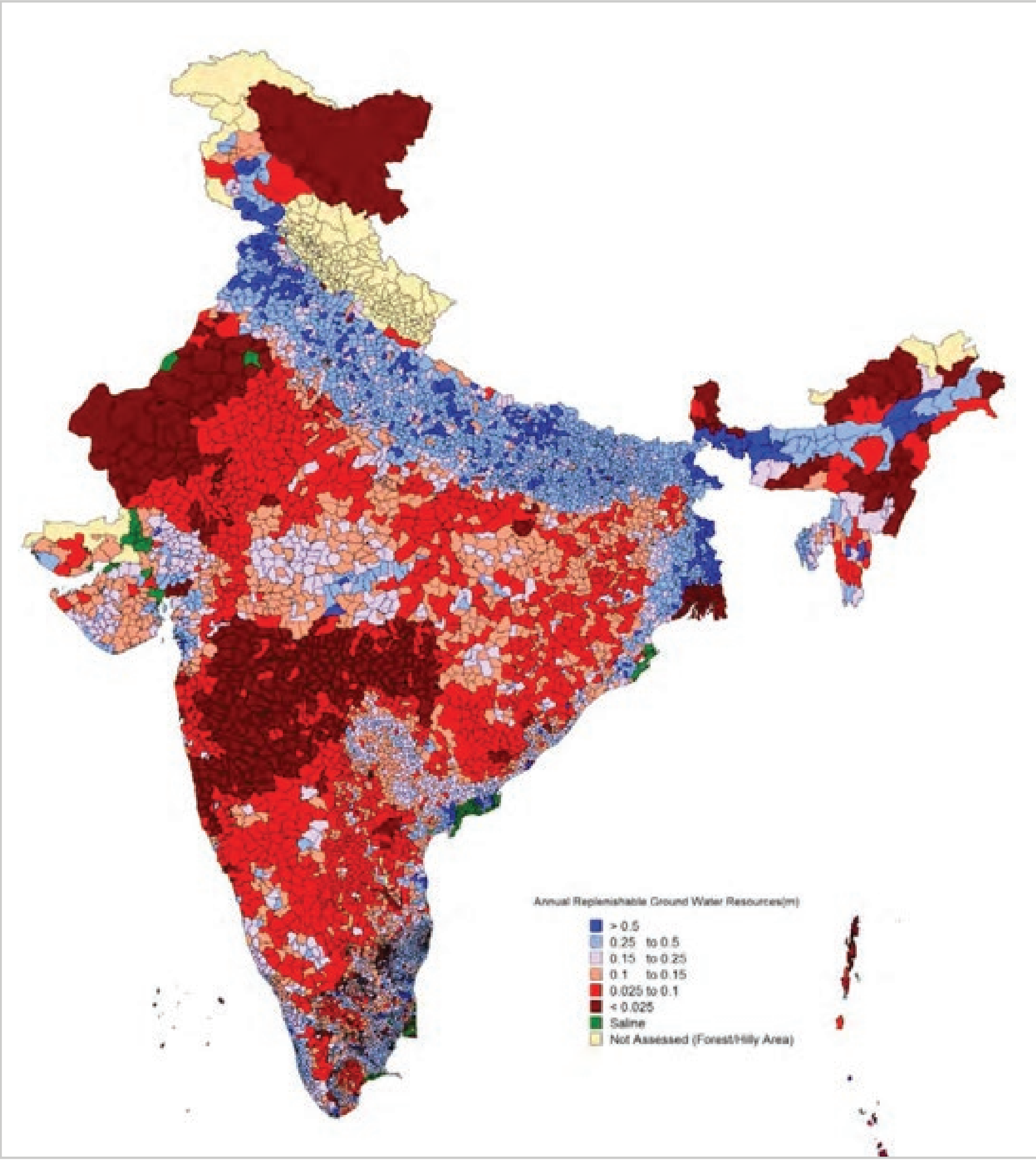

Exhibit 16. Annual replenishable groundwater resources vary strongly from place to place, depending on precipitation and geology. In the figure, regions with ample groundwater are blue, while regions with little groundwater are dark red. Abundant replenishable groundwater resources are found in the alluvial formations of the Indo-Gangetic basin, while less groundwater is found in hard rock regions of peninsular India. (Source: CGWB 2014)

Most of peninsular India is underlain by geologic formations often referred to as "hard rock". This is a generic term applied to igneous and metamorphic rocks such as granites, basalts, gneisses, and schists. Western Pakistan, though part of the Eurasian tectonic plate, shares similar hydrogeological conditions.

In hard rock regions, limited quantities of groundwater are stored in the weathered soil and sub-soil layers (typically tens of meters deep) that overlay the bedrock. The bedrock itself has zero "primary porosity", but has limited "secondary porosity" due to cracks and fissures where groundwater may enter. The storage volume for groundwater in hark rock regions is thus very limited, confined to the shallow soil layer and some deeper cracks, and may deplete seasonally upon heavy pumping.

Groundwater in hard rock is characterised by limited productivity of individual wells, unpredictable variations in productivity of wells over relatively short distances, and poor water quality in some areas. In hard rock regions, groundwater supply is limited and discontinuous, thus may not be available regardless of the number or depth of borewells.

Groundwater over-extraction in hard rock regions leads to rapidly falling water tables and seasonal depletion, imposing hard limits on groundwater extraction rates. In some regions of peninsular India, rising demand for groundwater vastly exceeds annually recharged amounts, leading to rapidly falling water table and many wells that are seasonally or permanently dry. Due to the high density of wells, interference between wells is common in hard rock areas, where neighbouring wells compete for limited groundwater.

3.3 Groundwater over-extraction in alluvial regions causes long-term decline of water table

In contrast to hard rock regions, alluvial regions have thick porous aquifers that contain large amounts of groundwater. Thick and unconsolidated alluvial formations that are conducive to recharge are found in the Indus-Ganges-Brahmaputra basins in Pakistan, northern India and Bangladesh. The coastal alluvial belt on the eastern coast of India also has relatively high replenishable groundwater resources.

Within the alluvial aquifers of the Indus-Ganges-Brahmaputra basin, there is a strong distinction between the relatively arid northern region and the more humid eastern region. Groundwater over-extraction in the northern region is leading to steadily falling water tables, gradually requiring deeper wells and increased pumping effort (see Exhibit 17).

This primarily affects the Punjab region in India and Pakistan, as well as western Rajasthan, northern Gujarat, and Haryana states in India, where water tables in some areas are declining by about 1 meter per year.

Depending on the water table decline rate and the aquifer thickness, groundwater over-extraction can continue for many years. Alluvial formations in the Indus-Ganges basins are hundreds or even thousands of meters thick. As technologies for deep well drilling are available, the constraining factor is the additional energy needed for pumping as the water table becomes deeper (see Exhibit 18). Although abundant groundwater stores now exist in these alluvial formations, the extraction and use of this stored water for current and near-future requirements raises questions of intergenerational equity and how future generations of South Asians will access water.

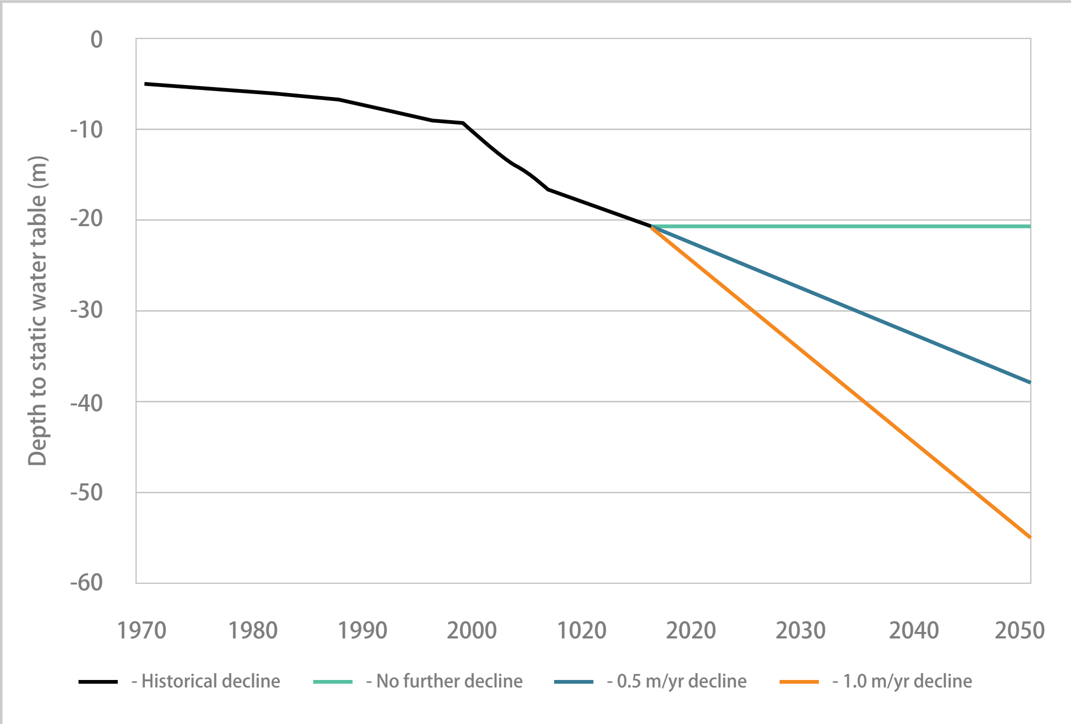

Exhibit 17. Historical and projected average depths to the static water table in Punjab, India. Projected depths assume no further decline (green line), 0.5m/yr decline (blue line) and 1.0 m/yr decline (orange line). See Exhibit 18 for implications of future decline rates. (Source: historical data from Singh 2011, CGWB 2015b, Dhiman et al. 2015)

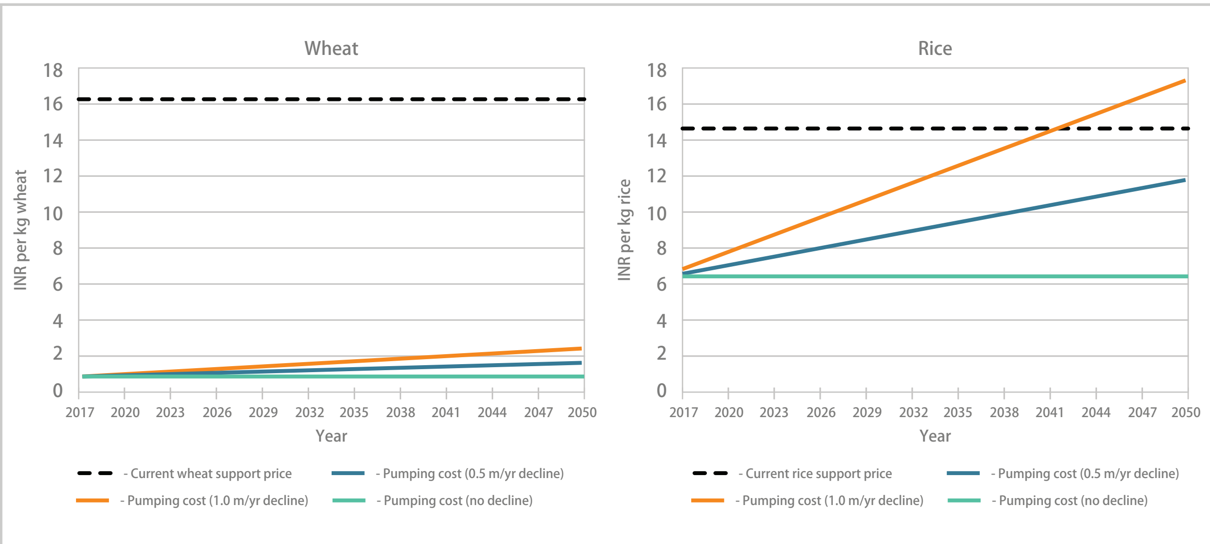

Exhibit 18. The real costs of pumping groundwater for rice irrigation are substantial. If standard domestic electricity tariffs were applied for groundwater pumping energy, the current pumping cost would equal about half of current GoI Minimum Support Price for rice, and would rise further as water table depths fall further. (Source: ITT analysis based on typical domestic electricity tariff of INR 5.20 per kWh, average pump set efficiency of 30% (Kaur et al. 2016), water productivity of 1.36 and 0.19 kg grain per m^3 of applied irrigation water for wheat and rice, respectively (Hussain et al. 2003; CACP 2015), and grain prices based on 2017 GoI Minimum Support Prices)

Groundwater remains abundant in the eastern Ganges and Brahmaputra regions, which have greater rainfall. In these regions, the phenomenon often described as the Ganges Water Machine operates (Revelle & Lakshminarayana 1975; Amarasinghe et al. 2016). The more groundwater that is withdrawn before the onset of the annual monsoon, the more soil pore space is created for water to recharge. This was confirmed to occur by Shamsudduha et al. (2011), who found that increased groundwater extraction has increased the overall extent of groundwater recharge in Bangladesh during recent decades.

Thus, in the eastern Ganges and Brahmaputra regions, groundwater from alluvial aquifers does not face the problem of over-extraction and is unlikely to face it in the future. Groundwater from these aquifers can be used for irrigation as a poverty alleviation tool, though at present this is hindered by economic water scarcity, which is described in detail in Section 3.12.

3.4 Faecal contamination of water bodies causes health and environmental impacts

Human faecal matter can contain a range of harmful pathogens, including viruses, bacteria, protozoa, and helminths (see Exhibit 19). These pathogens cause diarrhoea and other diseases, resulting in hundreds of thousands of deaths annually in South Asia, primarily among children (UNICEF 2017). People typically become infected by ingesting the pathogens, thus faecal contamination of surface and groundwater significantly increases the likelihood of infection. Faecal pathogens colonise the human gut, where they then grow and replicate.

Their transmission begins when the individual carrying the pathogen(s) defecates. From the point of defecation, the faecal pathogens may come into contact with another person via several transfer pathways, including surface and ground water, flies, crops, and the soil - where they then enter the body through drinking water, food, or from dirty hands (see Exhibit 20).

Continued exposure to faecal contamination can lead to chronic conditions such as malnutrition and stunting in children due to environmental enteropathy, in which the body uses much of the energy and nutrients from food to fight off ingested faecal pathogens, rather than absorbing them for growth and development (Harris et al. 2017). Stunted height indicates that vital organs, such as the brain and kidneys, are not developing properly and has been associated with a lower intelligence quotient (IQ) and a higher risk of developing diseases later in life (Schmidt 2014).

Pathogen type	Important pathogens	Characteristics
Viruses	**Rotavirus**	Viruses are infectious pathogens that can only replicate after infecting other living cells. Rotavirus is the single most important pathogen associated with diarrheal disease.
Bacteria	***ST-Enterotoxigenic E. coli, Shigella, Aeromonas, V. cholera, C. jejuni***	Bacteria can grow on food and in water and sewage under the right conditions. Some bacteria are seasonal, with major spikes in the wet season.
Protozoa	***Cryptosporidium Parvum***	Protozoa are advanced organisms that are transmitted through cysts that are extremely robust, able to survive for long periods outside of the body and resistant to chlorine purification.
Soil-transmitted Helminths	**Roundworm (*Ascaris lumbricoides*), whipworm (*Trichuris trichiura*), hookworm (*Necator americanus*** and ***Ancylostoma duodenale*)** and certain types of **tapeworm (*Taenia*)**	Soil-transmitted helminths (STH) are parasites that do not cause diarrhea, but rather live in the body, generally the intestines, and cause enteric inflammation. Eggs must mature in soil before becoming infectious to humans, however, they are extremely persistent and can survive for weeks to months on crops and soil, and years in fecal matter.

Exhibit 19. Faecal waste contains four major types of pathogens: viruses, bacteria, protozoa, and helminths. (Source: ITT 2014)

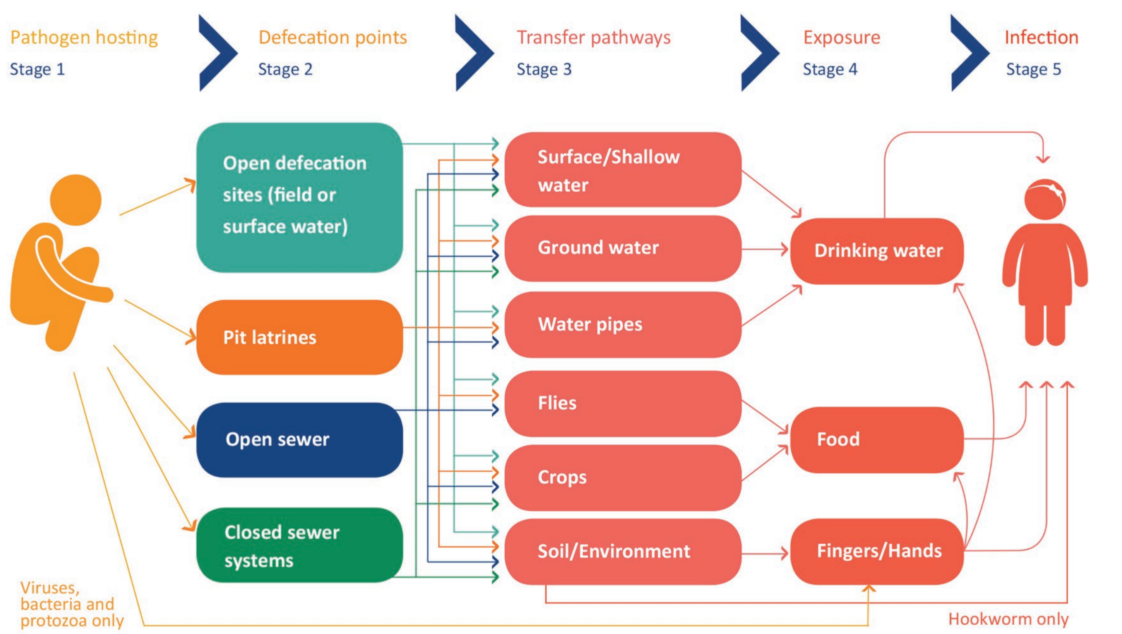

Exhibit 20. Faecal-oral pathogen flow model, showing multiple pathways for infection by faecal pathogens. (Source: ITT 2014)

Disposal of human faecal waste is a longstanding and ongoing challenge. Sanitation facilities were first introduced in South Asia around 2200 BCE in urban areas of the Indus Valley Civilisation. After the dissolution of that civilisation, South Asia reverted to smaller agrarian settlements that again practised open defecation (Schug et al. 2013). Public shared toilets were later constructed during the Mughal era in the 1500s (Jaglarz 2014). Between 1817 and 1923, six separate cholera pandemics each originated in the Ganges River delta near Kolkata in eastern India and spread throughout the world (CBC News 2008).

Investigation during the third pandemic in 1854 found that cholera was associated with unclean water, and a Royal Commission was appointed to assess the sanitary conditions of the British Army in India (Ramasubban 2008). A report published by the Royal Commission led to the creation of sanitary commissions in each of the Indian provinces (Anonymous 1869). Beginning in 1954, the central government of India implemented the first of several river conservation programs that focused on reducing the amount of wastewater entering rivers by setting aside funds to build sewage treatment plants (CPCB 2009).

Today, India's Swachh Bharat Abhiyan (Clean India Mission) aims to rid the country of open defecation through behaviour-change awareness programs and by subsidising the cost of each household's toilet.

Raw sewage flows into the Ganges River below Dapka Ghat in Kanpur.

Key sanitation indicators show positive long-term trends in South Asia, such as increasing access to improved sanitation facilities and decreasing rates of open defecation. Much effort has been made in recent decades to improve the sanitary conditions of South Asia. The number of people in India, Pakistan and Bangladesh with access to improved sanitation has increased by 146% from 2000 to 2015 (JMP 2017) (see Exhibit 21).

Also in the three countries, both the incidence rates of diarrhoea and the percent of under-five children who are stunted have decreased since the 1980s (see Exhibit 22 and 23). In India, the total number of episodes of diarrhoea per year in children under five decreased from 320 million in 1990 to 280 million in 2010 (Fischer-Walker et al. 2012, UNICEF 2017).

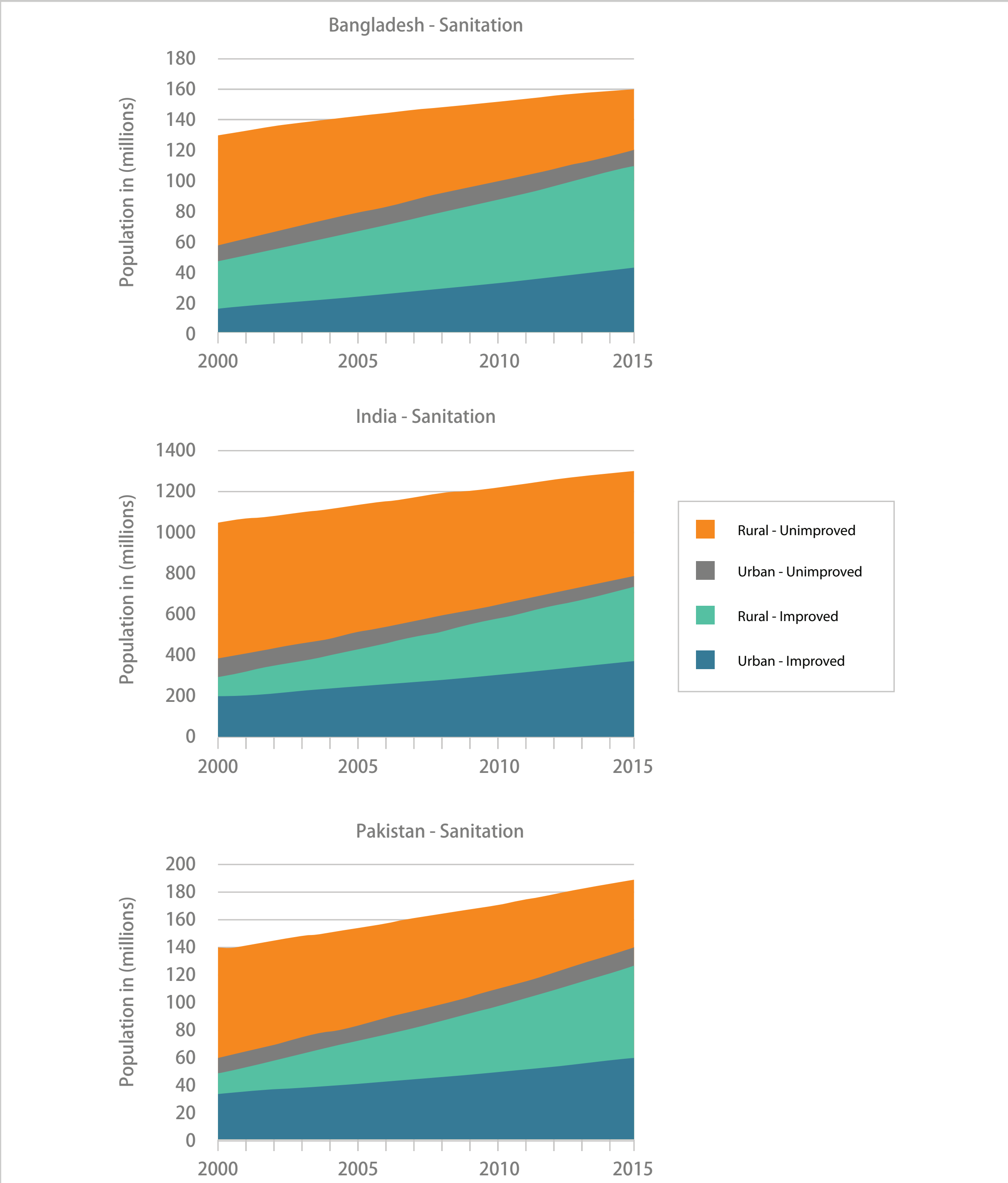

Exhibit 21. Throughout South Asia, the number of people with access to improved sanitation facilities has been rising, while the number of people with unimproved facilities has been falling. However, there are still many people without improved sanitation facilities, particularly in rural areas. (Source: data from JMP 2017; "Improved" and "Unimproved" sanitation is based on WHO/UNICEF JMP categories. Here, "Improved" sanitation includes Safely Managed, Basic, and Limited facilities; "Unimproved" sanitation includes Unimproved facilities and Open defecation.)

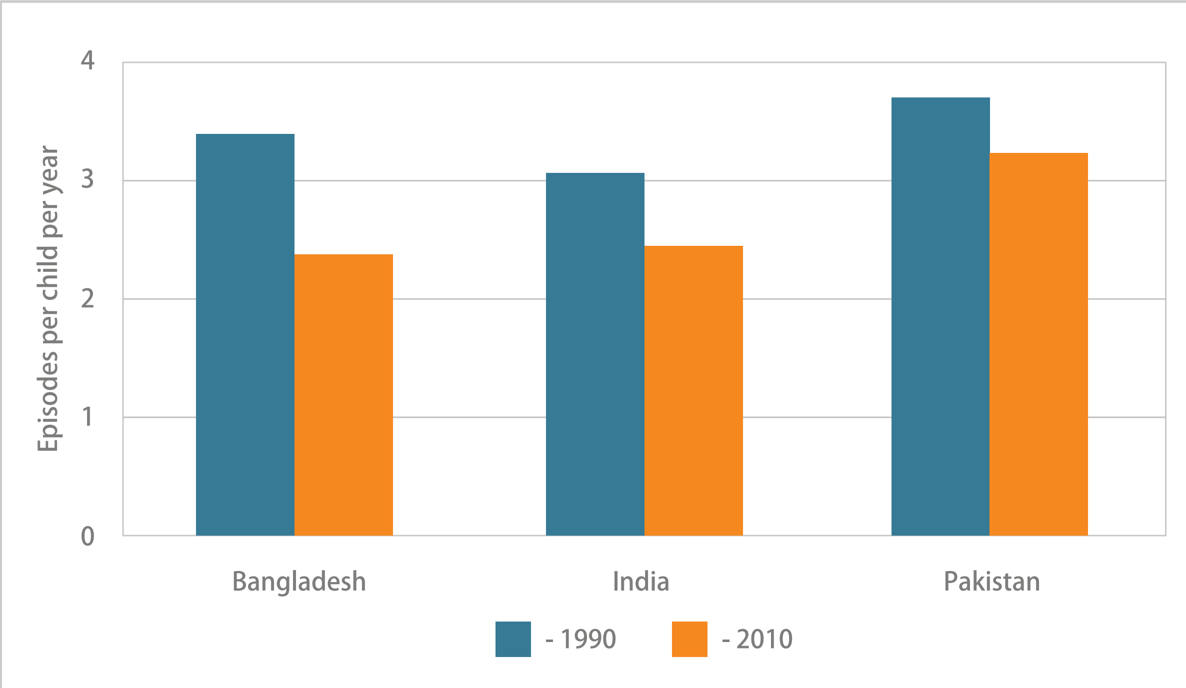

Exhibit 22. The rate of incidence of diarrhoea in children under 5 has been declining in Bangladesh, India, and Pakistan. (Source: data from Fischer-Walker et al. 2012)

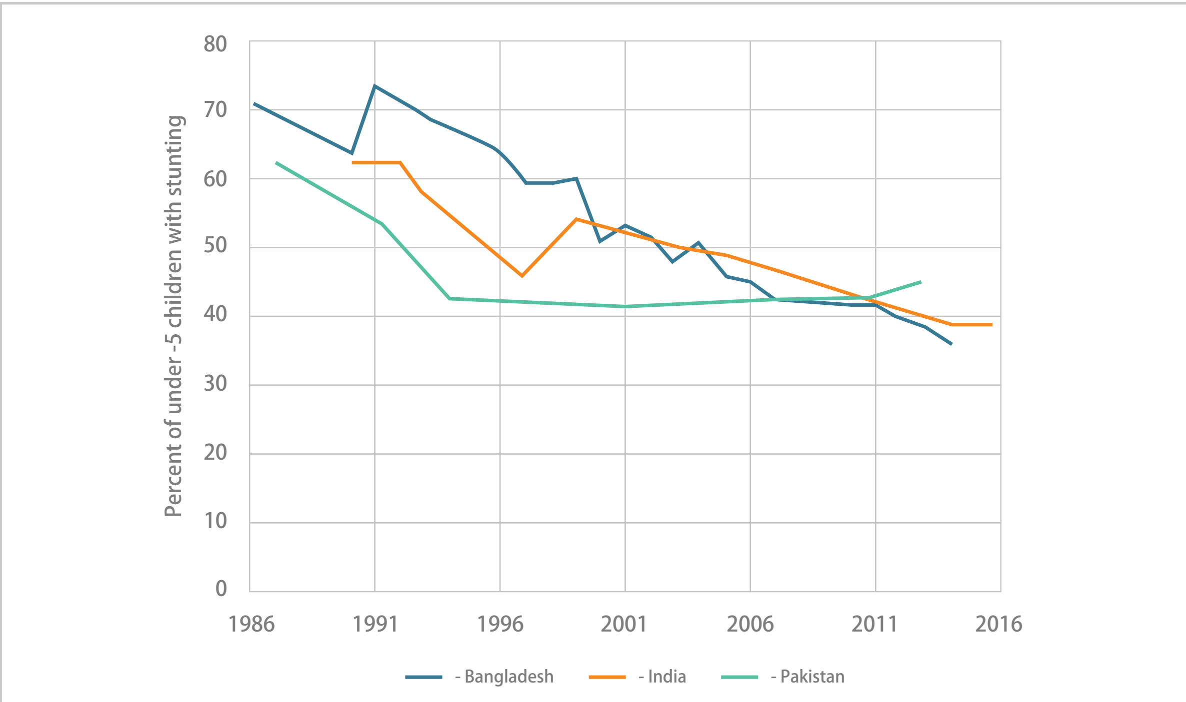

Exhibit 23. The percent of children in South Asia under five years old who experience stunting has declined during the last generation. (Source: data from UNICEF 2017)

Nevertheless, there are still huge numbers of people in South Asia that lack improved sanitation facilities or otherwise choose to defecate openly. This leads to contamination of water by faecal matter, which adversely affects public health, the environment, and the economy. In 2015, diarrhoea caused an estimated 34% of all deaths in children under five in South Asia (UNICEF 2017). Furthermore, aggregated estimates of access to clean water sources can be misleading, as "improved" water sources can also be contaminated with faecal bacteria (Bain et al. 2014).

At least two sorts of faecal pollution can be distinguished: rural and urban. In rural areas, open defecation is still commonplace, leading to direct faecal contamination of the surrounding environment (see Exhibit 24). This affects rural India in particular, where 56% of the population practises open defecation (JMP 2017).

Young men in Mumbai prepare to defecate in the open.

The practice has been in use for millennia and is culturally accepted, despite its detrimental health effects at current population densities. Idyllically envisioned as a regular opportunity for quiet contemplation in nature while completing biogeochemical cycles, open defecation becomes problematic when the amount of human waste exceeds the capacity for assimilation into the natural surroundings.

Open defecation was the norm during our species' long evolutionary history, and it was an effective sanitation strategy while population density remained low. As the number of people within the South Asian region increased (see Exhibit 10), the continuation of open defecation has led to spatial concentrations of human faecal waste at unpleasant and unhealthy levels.

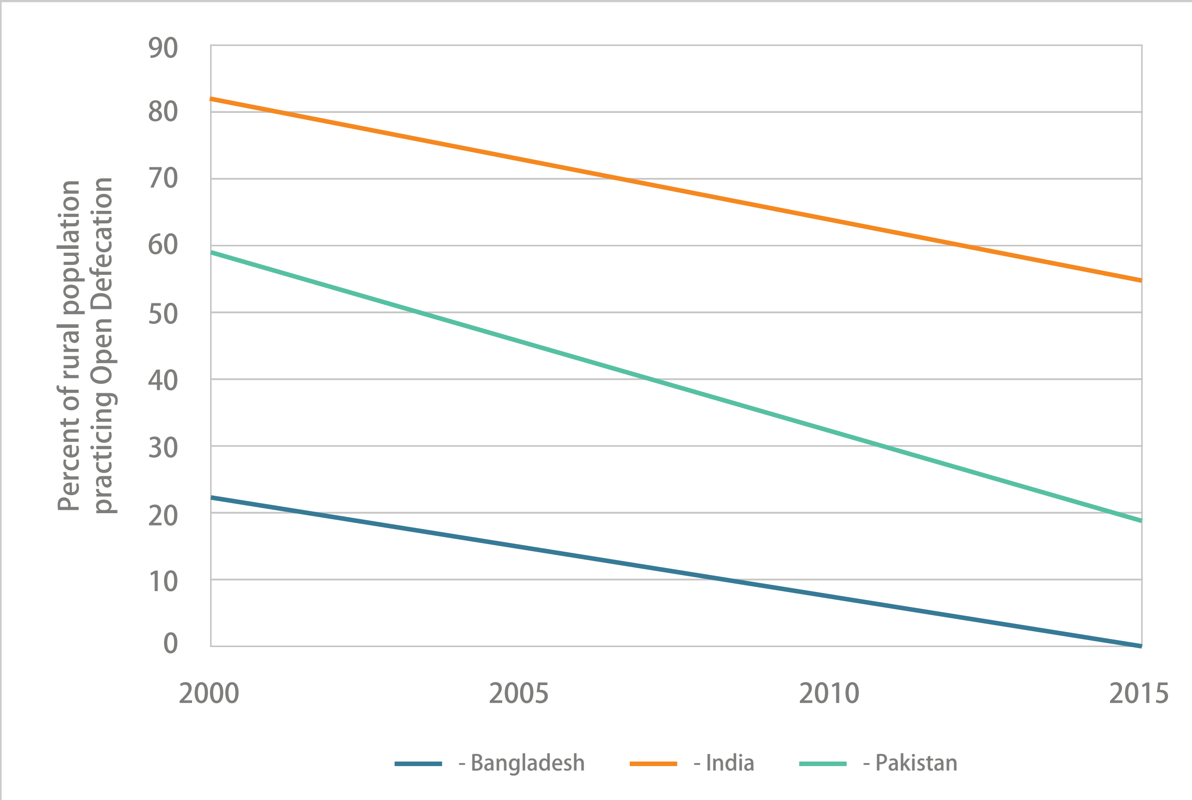

Exhibit 24. Despite significant reduction in open defecation during recent decades, over half of the rural population of India continues to practise open defecation. It is less prevalent in Pakistan and quite uncommon in Bangladesh. (Source: data from JMP 2017)

Urban faecal pollution is largely caused by untreated wastewater from sewage networks discharging into surface water bodies near cities (Kotloff et al. 2013). Wastewater treatment plants currently treat only about 38% of all wastewater generated in Indian cities (CPCB 2015) (see Exhibit 25). Thus, 62% of the collected sewage, over 14 km^3 per year, flows untreated into Indian rivers (CPCB 2015).

This is due to a lack of installed capacity as well as a lack of maintenance and operation of existing plants. In Bangladesh, only 17% of collected sewage is treated, however the discharged sewage is diluted more effectively due to the relative water abundance of Bangladesh (WWAP 2017). An additional source of faecal pollution is urban open defecation, which places the entire urban population at risk even if it is practised by a small percentage of residents. Crowding in cities further exacerbates the risks associated with untreated sewage and urban open defecation.

Despite progress in access to sanitation facilities and in improved human health outcomes, the high organic and nutrient loads placed on rivers in South Asia are increasing, resulting in significant ecological disruption. The high organic load in faecal waste and other domestic effluents leads to a high biochemical oxygen demand (BOD) of the water. The high nutrient load (primarily nitrogen and phosphorus) in the sewage results in eutrophication of water bodies, which is ecologically destructive and leads to anoxia and dead zones.

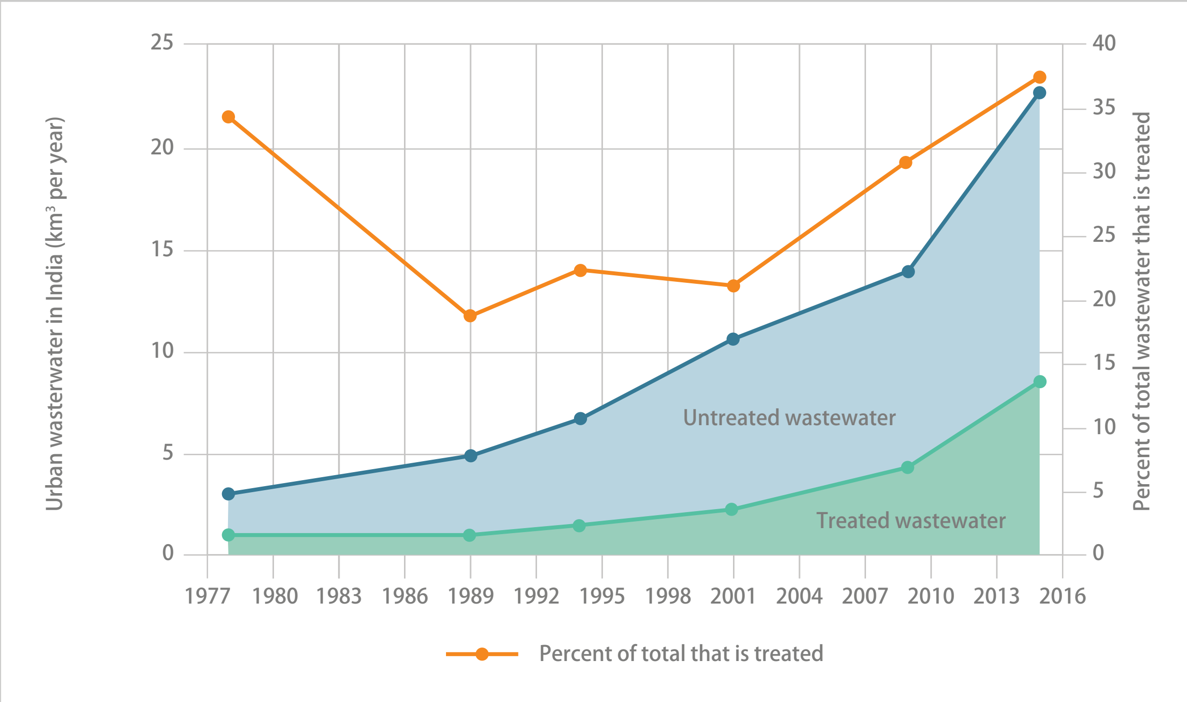

Exhibit 25. Despite the rapidly growing capacity of sewage treatment facilities in India, less than half of total wastewater collected is treated prior to discharge. Rapid growth in total wastewater collection in India is due to the rise in urban population and the increase in percent of urban households with sewer connections. (Source: data from CPCB 2005, 2009, 2015)

These impacts are described in more detail in Section 3.6. In 2015, more than 550,000 tons of nitrogen (N) and 160,000 tons of phosphorus (P) entered India's water bodies from sewage (see Exhibit 86). Large algal blooms and hypoxia characterise the Arabian Sea, where a recent change in algal species is thought to have resulted from the massive organic and nutrient loads entering the sea from Karachi, Mumbai, and other cities along the coasts of India and Pakistan (Gomes et al. 2014). Additionally, sewage discharge has resulted in sedimentation of rivers and oceans, which disrupts the natural ecosystem and kills aquatic plants (Gearing et al. 1991).

Faecal contamination of water bodies imposes great economic cost on societies, mainly from healthcare expenses and health-related opportunity costs. Indirect costs arise when water bodies are too contaminated to use. Worldwide, the UN projects that for every USD 1 spent on sanitation, over USD 5 in value is returned to society (WWAP 2017).

India is estimated to spend over USD 15 billion per year in treating waterborne diseases alone (HPEC 2011). Taking into account both monetary costs (e.g. healthcare costs, fuel consumption for boiling water) and nonmonetary costs (e.g. time spent taking care of patients and caring for the ill, opportunity cost from absenteeism at work and school, the value of loss of life), the total annual cost of poor sanitation is estimated to be USD 4.2 billion in Bangladesh, USD 5.7 billion in Pakistan, and USD 53.8 billion in India (WSP 2011, 2012, 2013).

3.5 Arsenic and fluoride contamination of groundwater causes health impacts

In some regions of South Asia, the underground geological formations comprise minerals containing arsenic or fluoride. Arsenic-bearing formations are prevalent in much of southern Bangladesh, the Indus basin of Pakistan, and the Indian states of West Bengal, Bihar and Uttar Pradesh, due to the long-ago deposition of silt from the Himalayas containing arsenopyrite (see Exhibit 26).

Groundwater in these areas naturally contains these elements. Until recent decades they caused no problems, because groundwater from deeper strata was largely inaccessible. Prior to the 1960s-70s, surface water or shallow well water was typically used for household consumption. As surface waters in rivers, lakes and ponds became more polluted by sewage (described in Section 3.4), borewells were widely constructed to access deeper unpolluted groundwater in order to avoid diarrhoeal diseases. This inadvertently resulted in wide exposure to arsenic in drinking water (Smith et al. 2000). In the Indus Valley in Pakistan, arsenic is also mobilised by elevated-pH dissolution resulting from alkaline topsoil and extensive irrigation, thus entering groundwater (Podgorski et al. 2017).

Arsenic is one of the elements on the Periodic Table (atomic number 33) and is quite mobile in the environment. Arsenic exists in several forms, but the most prevalent forms found in groundwater are arsenite [As(III)] and arsenate [As(V)] (Nicomel et al. 2016). Consumption of water, including both drinking water and cooking water, with elevated arsenic levels over a prolonged period can result in serious health conditions, including skin lesions, hyperkeratosis, melanosis, and cancer in different organs, which in some cases has been fatal (NIH 2017). The probability and severity of health effects increase with exposure level and exposure duration.

Beginning in the 1980s-90s, chronic diseases were observed among households using water containing arsenic and fluoride. The first cases related to arsenic-contaminated water were observed in the early 1980s in Bangladesh and West Bengal and first reported in the medical literature in 1984 (Garai et al. 1984). The problem of arsenic-contaminated groundwater was further documented during the 1980s and 1990s, and in 2000 it was declared by World Health Organization researchers as “the largest mass poisoning of a population in history” (Smith et al. 2000). There is substantial uncertainty around the number of people affected by arsenic and large variation in the level of exposure. Estimates of affected populations are necessarily broad and range from 35-80 million people in Bangladesh, 50-200 million in India, and 50-60 million in Pakistan (Smith et al. 2000; Argos et al. 2010; Chakraborti et al. 2013; Podgorski et al. 2017).

Both the WHO and the USEPA specify that no more than 10 μg/L (10 ppb) of arsenic can be present in drinking water for safe consumption. This is known as the maximum contaminant level (MCL). While the maximum contaminant level goal (MCLG) of arsenic is 0 μg/L, MCLs are set as close to the MCLG as possible considering costs, benefits, and the ability to detect and remove arsenic. It is very difficult to detect arsenic levels below 10 μg/L with current measurement technologies.

Photo by Mike Lusmore/Duckrabbit of WorldFish

A farmer transplants rice in Bangladesh

While the health effects of arsenic-contaminated drinking water are becoming better understood, there is more uncertainty regarding the impacts of using arsenic-contaminated groundwater for irrigation. Studies show little correlation between arsenic in irrigation water and arsenic in produce such as rice, vegetables, fruits, and pulses (Senanayake and Mukherji 2014; Bhattacharya et al. 2010). The amount of arsenic available for crop uptake is influenced by multiple factors including soil redox potential, pH, organic matter content, soil microbes, and the levels of iron, manganese, phosphorus, and calcium carbonate in the soil.

Arsenic that is taken up by plants tends to accumulate primarily in the plant roots with progressively less accumulating in stems, leaves, and grains. Thus, root vegetables, such as potatoes, accumulate a higher amount of arsenic than other crops. The most important impact of irrigation with arsenic-contaminated water may be the significant long-term reduction in yields (Huhmann et al. 2017).

Fluoride is an anion of the element fluorine (atomic number 9) with the chemical formula F^- and occurs naturally in some groundwater. It is reported that over 66 million people in India are exposed to high concentrations of fluoride in groundwater (Mumtaz et al. 2015). The worst affected areas of India include Rajasthan, Gujarat, Telangana and Andhra Pradesh states.

When present in drinking water at concentrations of 0.8-1.0 mg/L, fluoride is beneficial for calcification of dental enamel, thus reducing tooth decay. At higher concentrations (1.5-2.0 mg F/L), fluoride has adverse effects and leads to dental fluorosis. At still higher concentrations (3-6 mg F/L), skeletal fluorosis occurs, affecting bones and ligaments.

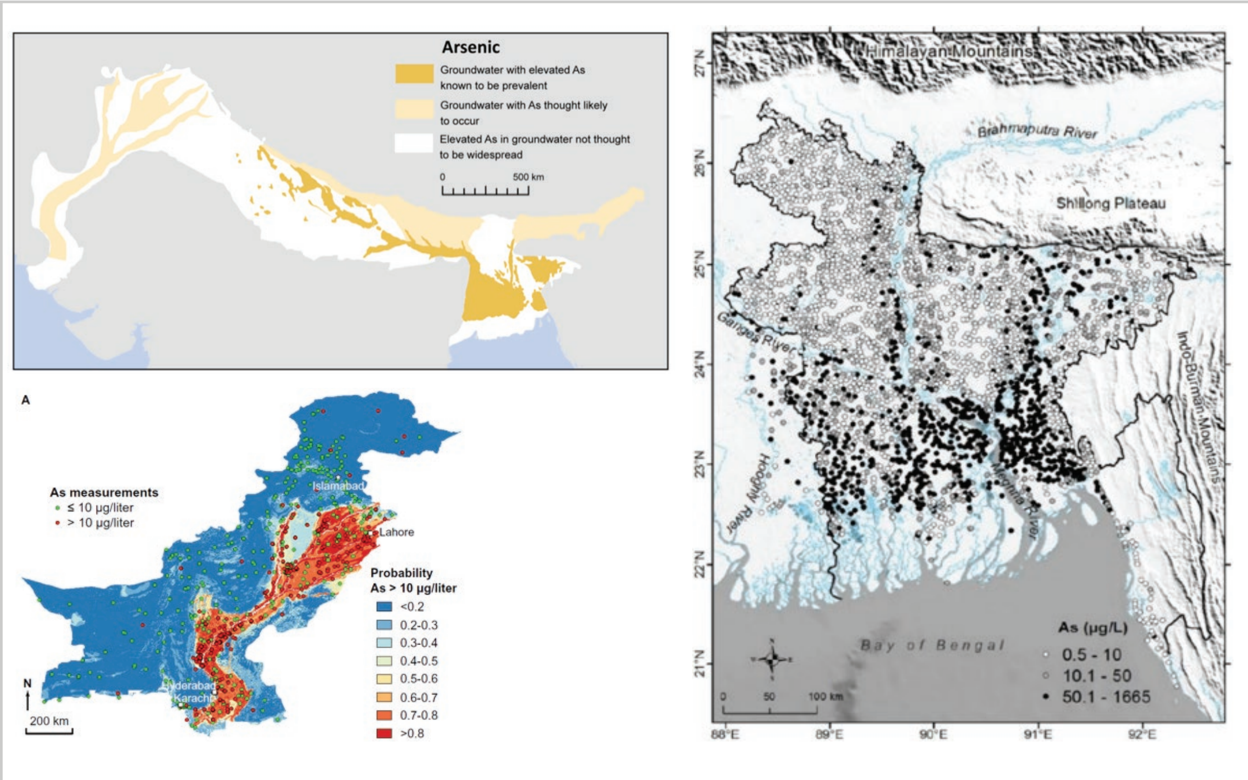

Exhibit 26. Groundwater supply in some regions of South Asia is contaminated by arsenic. Top left figure shows the presence of arsenic in groundwater in the Indus-Ganges-Brahmaputra aquifer system (Source: BGS 2015). Right figure details arsenic concentrations in shallow (<150 m bgl) groundwater in Bangladesh (Source: Shamsudduha 2013). Bottom left figure shows the probability of occurrence of arsenic concentrations in groundwater in Pakistan that exceed the WHO guideline of 10 µg/L (Source: Podgorski et al. 2017).

3.6 Diverse industrial effluent and agricultural run-off cause health and environmental impacts

Rapid industrial and agricultural expansion in South Asia during recent decades has resulted in a diverse range of chemical contaminants that increasingly pollute surface and groundwater. Industrial effluent is typically concentrated point source pollution from individual facilities, while agricultural run-off is diffuse non-point source pollution originating across large areas.

Industrial pollution is generally increasing in South Asia as the overall industrial production in numerous diverse industrial facilities grows faster than the adoption of best-practice cleaner industrial processes. Effluent is discharged from a range of industrial sectors: distilleries, sugar, textiles, electroplating, pesticides, pharmaceuticals, pulp and paper, tanneries, dyes, petrochemicals and steel (see Table 2). These effluents are diverse and contain a wide range of chemical and biological contaminants with potential human health effects.

Industry	Typical content of effluent
Pulp and paper	• Chlorinated lignosulphonic acids, chlorinated resin acids, chlorinated phenols and chlorinated hydrocarbons - about 500 different chlorinated organic compounds identified • Coloured compounds and absorbable organic halogens (AOX) • Pollutants characterized by BOD, COD, suspended solids (SS), toxicity and colour
Iron and steel	• Cooling water containing ammonia and cyanide • Gasification products - benzene, naphthalene, anthracene, cyanide, ammonia, phenols, cresols, and polycyclic aromatic hydrocarbons • Hydraulic oils, tallow and particulate solids • Acidic rinse water and waste acid (hydrochloric and sulphuric)
Mines and quarries	• Slurries of rock particles • Surfactants • Oils and hydraulic oils • Undesireable minerals, i.e. arsenic • Slimes with very fine particulates
Food industry	• High levels of BOD and SS concentrations • Variable BOD and pH depending on vegetable, fruit or meat and season • Vegetable processing - high particulate, some dissolved organics, surfactants • Meat - strong organics, antibiotics, growth hormones, pesticides and insecticides • Cooking - plant organic material, salt, flavourings, colouring material, acids, akalines, oil and fat
Brewing	• BOD, COD, SS, nitrogen, phosphorus - variable by individual processes • pH variable due to acid and alkaline cleaning agents • High temperature
Dairy	• Dissolved sugars, proteins, fats and additive residues • BOD, COD, SS, nitrogen and phosphorus
Organic chemicals	• Pesticides, pharmaceuticals, paints and dyes, petro-chemicals, detergents, plastics, etc. • Feed-stock materials, by-products, product material in soluble or particulate form, washing and cleaning agents, solvents and added-value products such as plasticizers
Textiles	• BOD, COD, metals, suspended solids, urea, salt, sulphide, H_2O_2, NaOH • Disinfectants, biocides, insecticide residues, detergents, oils, knitting lubricants, spin finishes, spent solvents, anti-static compounds, stabilizers, surfactants, organic processing assistants, cationic materials, colour • High acidity or alkalinity • Heat, foam • Toxic material, cleaning waste
Energy	• Extraction of fossil fuels - contamination from oil and gas wells and fracking • Hot cooling water

Table 2. Different industries produce effluents with a wide range of contaminants. (Source: adapted from WWAP 2017)

Farming practices associated with the Green Revolution use large amounts of fertilisers and pesticides; some of these run off from the farm and contaminate surface and ground water. Nitrogen and phosphorus fertilisers in water bodies can lead to eutrophication and toxic algal blooms.

Many agricultural pesticides are classified as persistent organic pollutants (POPs), which are organic compounds that do not degrade readily and therefore persist in the environment. They tend to bioaccumulate in organisms, meaning that they remain in individual organisms and accumulate over time. As smaller organisms are consumed by larger organisms, the POP concentrations increase with each trophic level. This becomes harmful to humans who consume upper trophic level fish.

Two particularly concerning types of environmental toxins are heavy metals and endocrine disruptors. Heavy metals are basic metal elements such as lead, mercury, cadmium and chromium. As elemental materials, they cannot be degraded or destroyed and also bioaccumulate in the body over time. Exposure to lead affects multiple body systems. Young children are particularly vulnerable to the toxic effects of lead and can suffer profound and permanent brain and nervous system damage.

An emerging threat from some contaminants is their potential impact to the human endocrine system. Some chemicals, including POPs and heavy metals, act as endocrine disruptors, interfering with the body's natural hormones. Even at very low levels of exposure, they may cause reproductive and other health problems in humans and animals, including infertility and early puberty.

Discharge of effluent with a high biological carbon content (from e.g. pharmaceutical, textile, pulp and paper industries, as well as from sewage) results in a high biochemical oxygen demand (BOD) when discharged into water bodies. Microorganisms rapidly decompose the organic material and use up large quantities of oxygen in the process, which depletes the surrounding environment of oxygen and leads to hypoxic conditions. The lack of oxygen can lead to the death of fish and other aquatic fauna.

When agricultural run-off makes its way into water bodies, the high loads of nitrogen and phosphorus are taken up readily by natural algae, which results in an explosion of the algal population, known as an algal bloom.

Blooms are problematic since they blanket the water's surface and block sunlight from reaching underlying aquatic plants, killing them. Once the algae die off, their decomposition leads to hypoxia and potentially anoxia, resulting in death of fish and other aquatic organisms. This phenomenon is common across India, and nitrate contamination of groundwater has been identified in southern Punjab.

Certain algal blooms release toxins that are deadly to humans, known as harmful algal blooms (HABs). HABs become dangerous when people consume seafood that has a high concentration of these toxins due to bioaccumulation. The number of HAB episodes off the coast of India increased 15% between 1998 and 2010, with the majority of blooms occurring in the Arabian Sea during the southwest monsoon and in the Bay of Bengal during the northwest monsoon (Padmakumar et al. 2012). This suggests that surface run-off during monsoon leads to increased frequency of HABs.

Reports of fish kills from pollution discharge and hypoxic/anoxic conditions have been frequent in South India in recent years (The Hindu 2016, 2017; The Times of India 2017). These events have deleterious effects on food security in some regions of South Asia. In Bangladesh, for example, 64% of the animal protein produced comes from inland fisheries. In India, over 1 million tonnes of inland fish are caught and consumed each year. Fishing is an important livelihood option for many people living in poverty, as it does not require advanced training or equipment (UNEP 2016).

3.7 Urban water demand from growing cities exceeds local supplies

Urban population in South Asia is projected to almost double between 2017 and 2050, due to a combination of overall population growth and increasing urbanisation (see Exhibit 27). Currently, urban population in India increases by about 10.3 million individuals per year (calculated based on UN 2017 and UN 2018). In Bangladesh and Pakistan, urban population is increasing by about 1.9 and 1.8 million people per year, respectively.

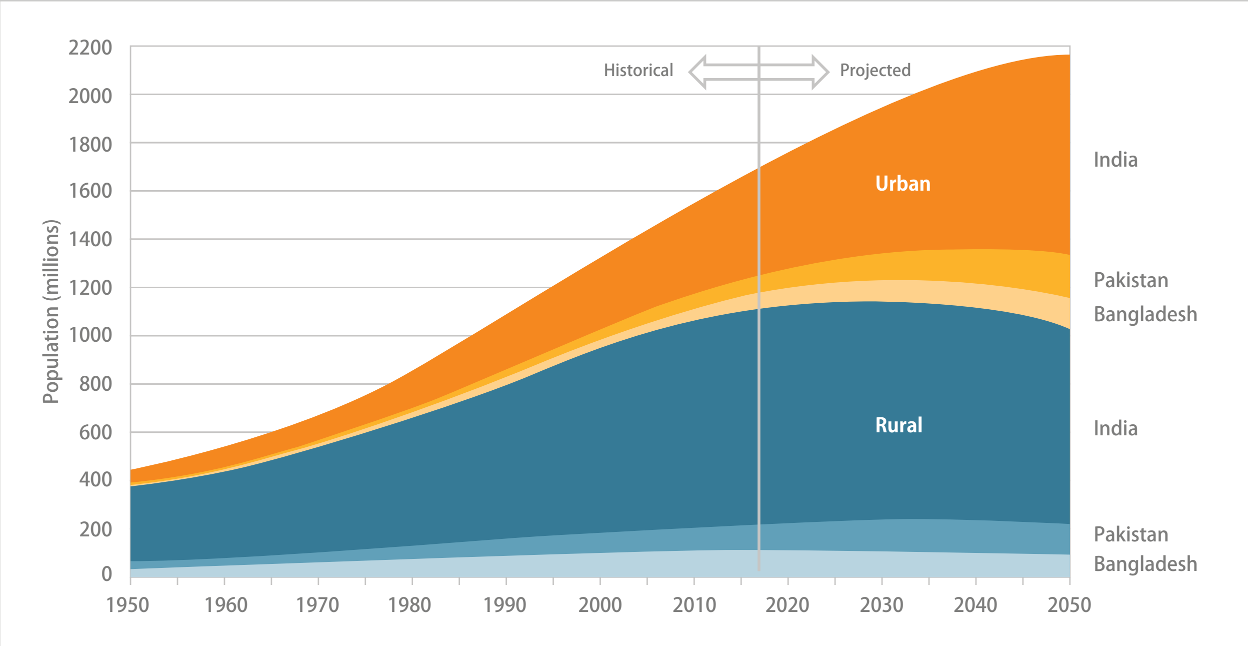

Exhibit 27. Urban population in South Asia is expected to double by 2050 due to rising total population as well as increasing urban proportion. (Source: data on total populations from UN 2017 medium fertility projection; data on urban proportions from UN 2018)

This increase in population is causing a rapidly growing demand for urban water consumption. Urban areas need water for both household use and industrial use. The Bureau of Indian Standards recommends a minimum of 135 litres per capita per day for communities with water-based (i.e. flushed) sanitation (BIS 1993). Surveys show actual water consumption among Indian households varies widely both geographically and socio-economically, with an average of about 92 litres per capita per day (see Exhibit 28).

Many industries located in urban areas also require water for various processes. Aggregated per capita urban water supply statistics mask the inequity between citizens, with the poorest residents barely securing water for subsistence, while the richest residents enjoy abundant water supply. This is described further in Section 3.12 on economic water scarcity.

A truck delivers water to households in an urban area.

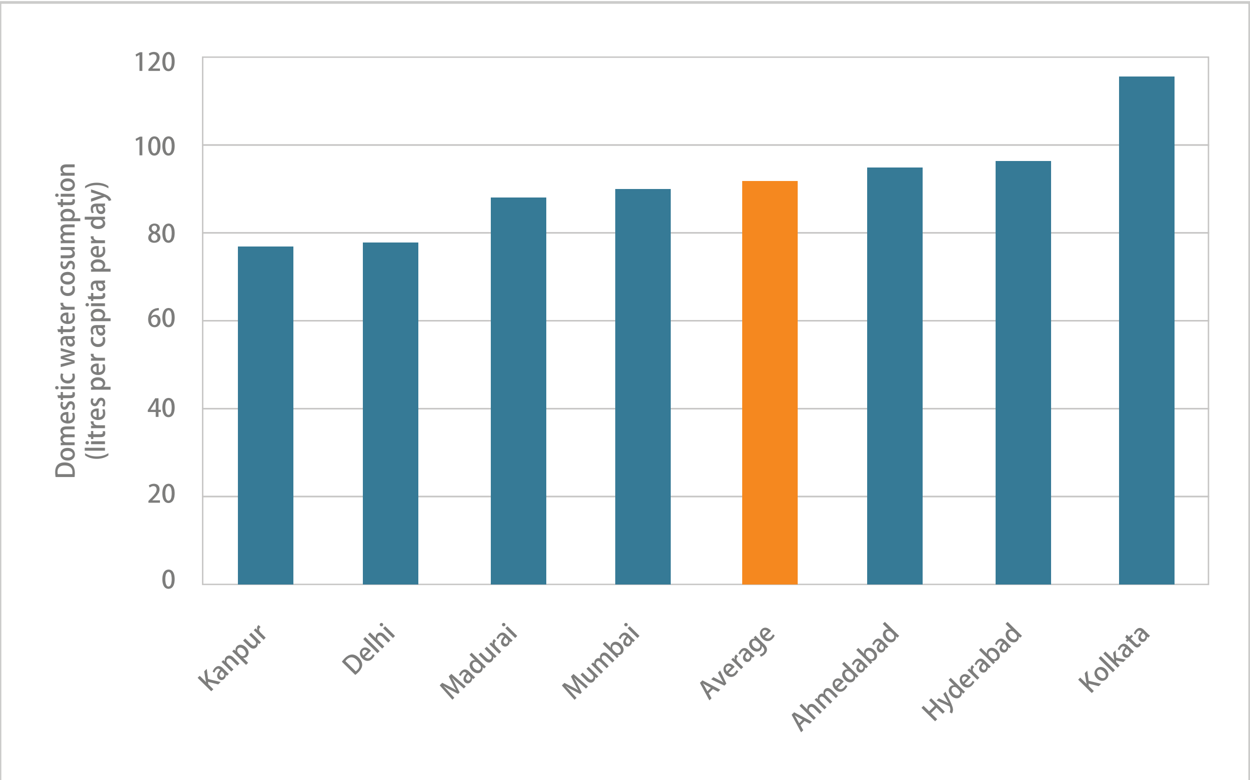

Exhibit 28. Per capita water consumption by households varies by city. Among the seven Indian cities surveyed, the average consumption was about 92 litres per capita per day. (Source: data from Shaban & Sharma 2007)

Although the absolute quantity of water supplied to urban residents is much smaller than that used by agriculture, water use in cities is concentrated with a high level of use in a relatively small geographic area (see Exhibit 29). Furthermore, each litre of urban water generates more value in social and economic terms than a litre of irrigation water.

This is because households require timely water access for essential household activities like drinking, cooking, cleaning and sanitation, and because industrial activities generate relatively high economic returns from water use. For example, urban health and hygiene depends on water for the functioning of modern sewage systems. An adequate and reliable supply of water to cities remains essential for civil living.

Within an area, cities tend to appropriate water from agriculture through many different formal and informal mechanisms, due to the absolute need for household water coupled with the economic concentration of urban population (Molle & Berkoff 2006).

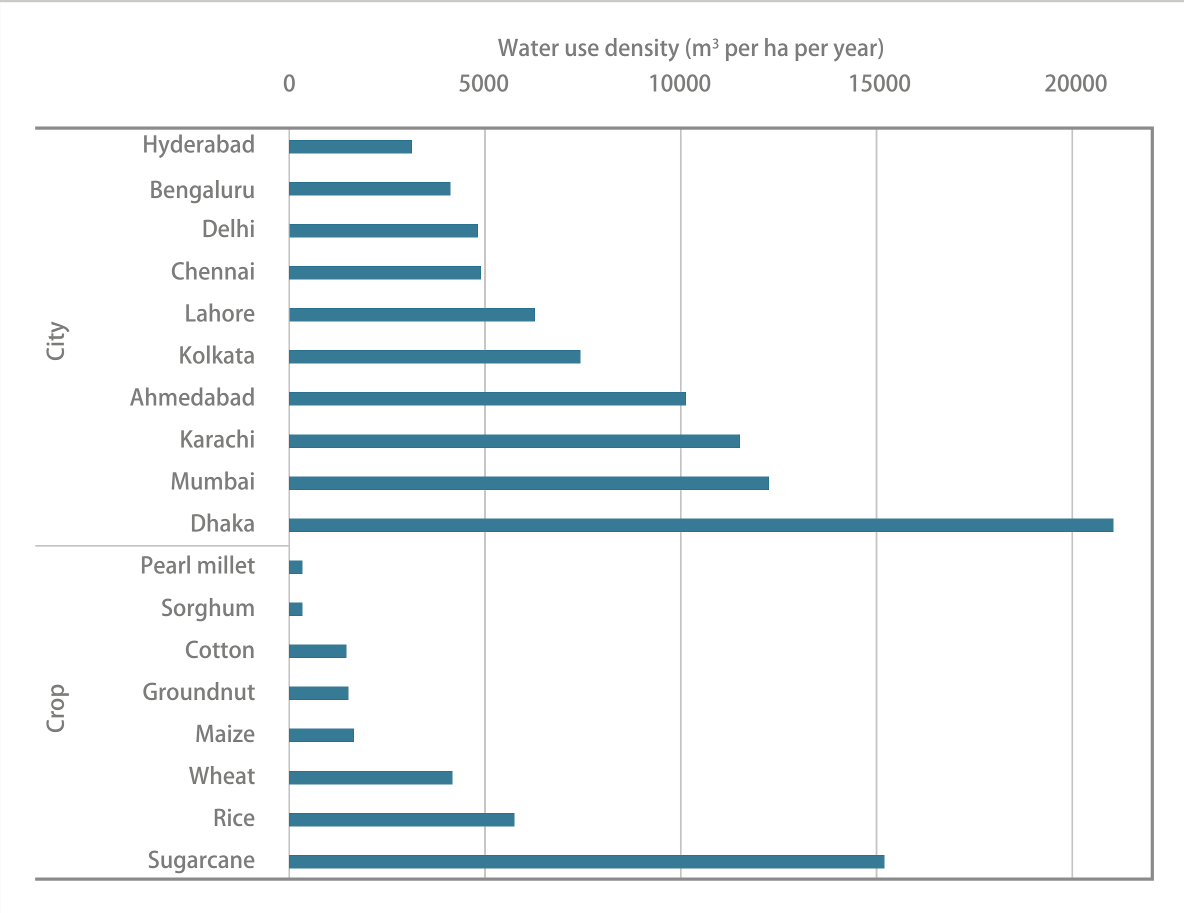

Exhibit 29. Cities tend to concentrate high water use in relatively small geographical areas. The household water use density (in units of m^3 of household water use per hectare of land area per year) of most major South Asian cities is higher than that of most irrigated agricultural fields. (Source: ITT analysis based on: For cities, population and land area data from Demographia 2016, per capita household water use data from Shaban & Sharma 2007, and assumed distribution losses of 30%. Urban industrial water use is not included, thus city water use is underestimated. For crops, water use density is based on all-India averages, with total cultivated area and irrigated area from India Ministry of Agriculture 2016, total crop water use from Hoekstra & Chapagain 2007, irrigation water application rate from Fishman et al. 2015.)

In addition to household use, another important demand for urban water is industries. Particularly water-intensive industries include steel, textiles, pulp and paper. Some industries, located in urban areas, use water from municipal supply systems. Other industries obtain water from local surface and groundwater sources (see Exhibit 30). In cities with water stress, this industrial water demand competes with household water demand to obtain adequate essential water supply.

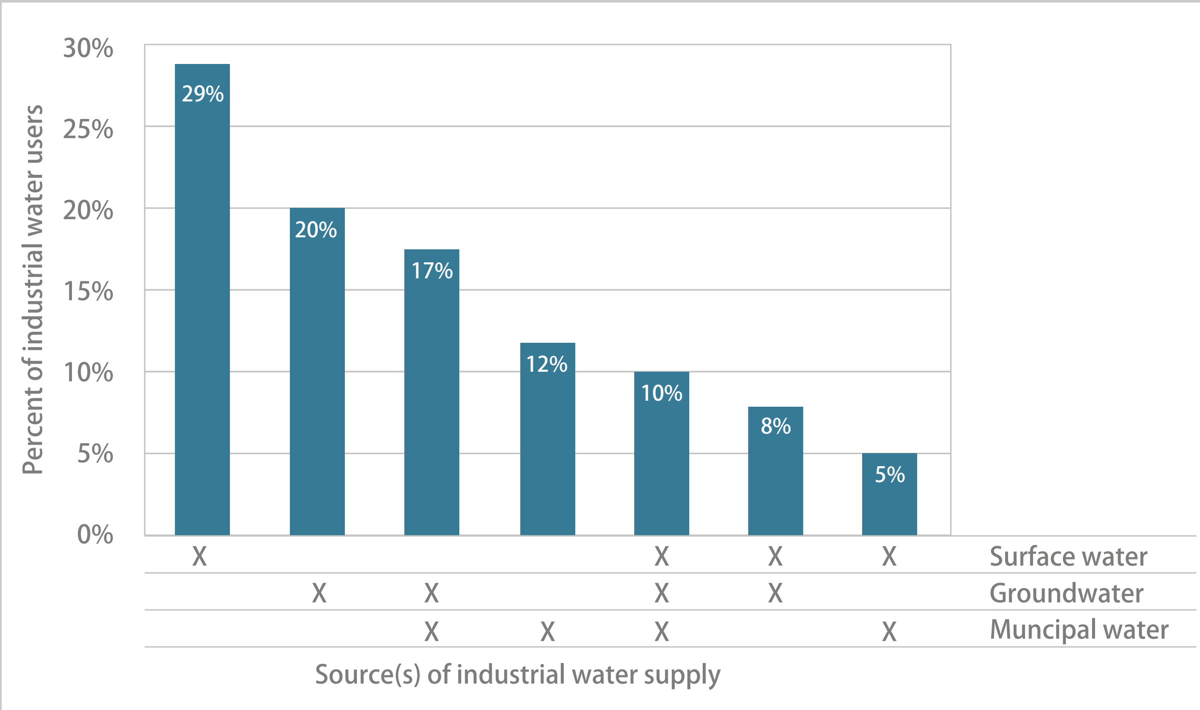

Exhibit 30. Industries access water from various sources, including surface water, groundwater and municipal water systems. (Source: data from Perveen et al. 2012, based on survey of Indian industries)

Many cities in South Asia already struggle to provide adequate water supply to their citizens. As noted in Sections 3.1-3.3, current water use in some regions is approaching or exceeds local sustainable supplies of surface and groundwater. Rapidly rising urban water demand from growing cities contributes to this overexploitation.

South Asian cities that are dependent on groundwater for municipal supply, such as Dhaka and Chennai, observe falling water tables requiring increased drilling and pumping costs. Cities that depend on surface water, such as Bengaluru and Hyderabad, face intermittent or insufficient supply. Reliable water supply is already challenging in many cities due to growing demand combined with aging and insufficient infrastructure (see Table 3).

Mismatch between urban water supply and demand will impact human development in several ways. First, the health of (poorer) urban populations will suffer, due to drinking contaminated water or unsanitary conditions resulting from water scarcity. Second, the economic potential of urban areas will be reduced, due to disproportionate spending by municipalities, households and industries to ensure adequate water supply.

City	Population (millions)	Rainfall (mm per year)	Primary sources of municipal water	Constraint to supply increase
Delhi	26	790	Eastern Yamuna and Upper Ganges Canals	Medium
Mumbai	23	2260	Upper Vaitarna and Middle Vaitarna Dams	Low
Karachi	23	220	Hub Dam, Haleji and Keenjhar Lakes	High
Dhaka	16	2120	Groundwater	Low
Kolkata	15	1800	Hooghly River from Ganges	Low
Lahore	10	630	Tarbela Dam from Indus River; Groundwater	Medium
Bengaluru	10	990	Kaveri and Arkavati Rivers	High
Chennai	10	1390	Kosasthalaiyar River; Groundwater; Desalination	High
Hyderabad TL	8	830	Musi, Krishna, Godavari, Manjeera Rivers	Medium
Ahmedabad	7	750	Narmada Canal; Groundwater	High

Table 3. Characteristics of the ten largest cities of South Asia and their municipal water supplies. (Source: population data from Demographia 2016; annual average precipitation from Wikipedia 2017; water source data from multiple sources; constraint to supply increase from ITT analysis)

3.8 Available water supply becomes brackish or saline from groundwater salinization

In regions that historically have had saline or brackish groundwater, as well as in coastal regions with access to sea water, salty water has long been present but has not typically been used as a water supply, except in some industrial applications. Permanent human settlements in these regions have depended on reliable access to a separate source of fresh water. Thus, the presence of saline or brackish water has not been a problem *per se*, although it has limited the available options for water supply. Naturally occurring saline groundwater is particularly prevalent in lower Pakistan and Bangladesh, and the Indian states of Gujarat and Rajasthan (see Exhibit 31).

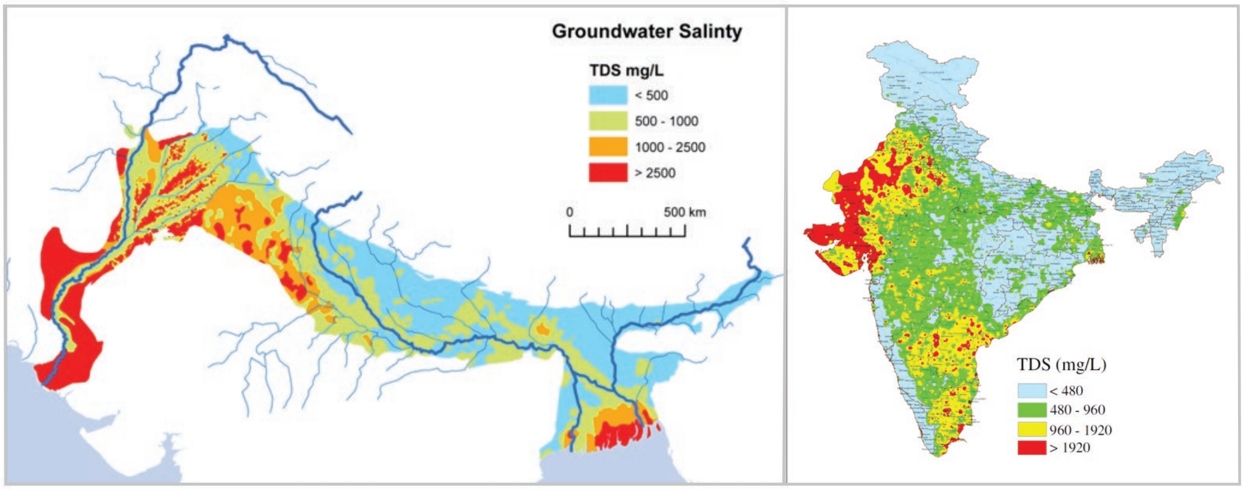

Exhibit 31. Groundwater supply in some regions of South Asia is contaminated by salt. Left figure shows the Indus-Ganges-Brahmaputra aquifer system (Source: BGS 2015). Right figure shows India (Source: CGWB 2010; units of salinity converted from EC to TDS).

More recently, some regions that historically had fresh groundwater supplies have suffered from salinization of their groundwater, i.e. the intrusion of salty groundwater into freshwater aquifers. This may have a range of causes, including sea level rise, overdraft of freshwater aquifers, river basin closure, and waterlogging of irrigated cropland. In these regions, the salinization of previously fresh water sources can have a significant impact on social wellbeing and economic activity. The salinization of coastal aquifers is particularly acute in the Saurashtra coast in Gujarat, the Minjur aquifer in Tamil Nadu, and the Sundarban region in coastal Bangladesh and West Bengal (see Exhibit 32).

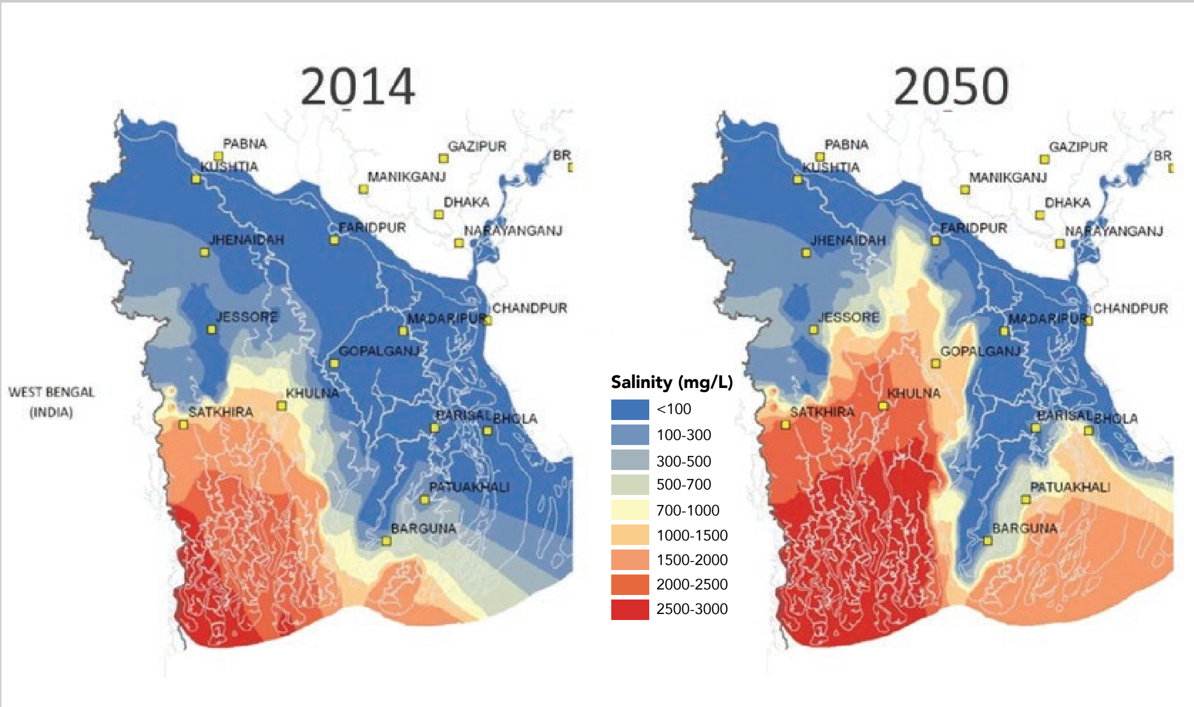

Exhibit 32. Groundwater in southwest Bangladesh is expected to become increasingly saline by 2050, due to salinity intrusion from rising sea level. (Source: adapted from CSIRO 2014)

3.9 Irrigated agricultural land becomes waterlogged and salinized over time

Successful agriculture requires adequate soil drainage, to allow excess water and salts to flow away from the plant root zone. When large-scale canal irrigation systems were initially designed and built in South Asia, natural drainage was adequate because the water table was typically many tens of metres below ground, allowing salts to drain into deeper soil.

Human hydraulic interventions in some areas during the past 150 years have substantially increased inflow to groundwater from canal leakage and irrigation drainage, thus altering the groundwater balance and causing water tables to rise in some places (see Exhibit 33). Soil in the lower reaches of some canal command areas is now often waterlogged. Within South Asia the worst affected region is the IBIS irrigation system in Pakistan, where about 24% of the total irrigated area is considered waterlogged, with a water table depth of less than 1.5 m (Zaman & Ahmed 2009). In Sindh province, in particular, over half of the irrigated area is waterlogged (see Exhibit 34).

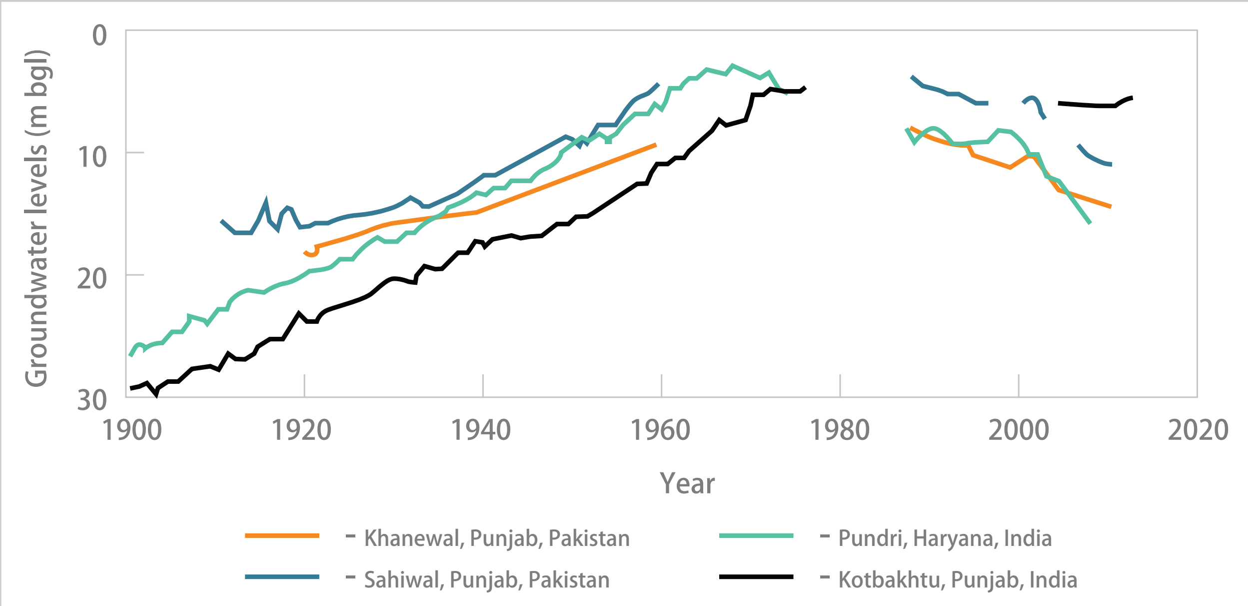

Exhibit 33. The introduction of large-scale irrigation systems has dramatically altered the groundwater balance of the Indus-Ganges basins. Water tables had been rising until the 1970s due to irrigation return flows and canal leakage. Water tables have since begun to fall due to intensive groundwater pumping. (Source: MacDonald et al. 2016)

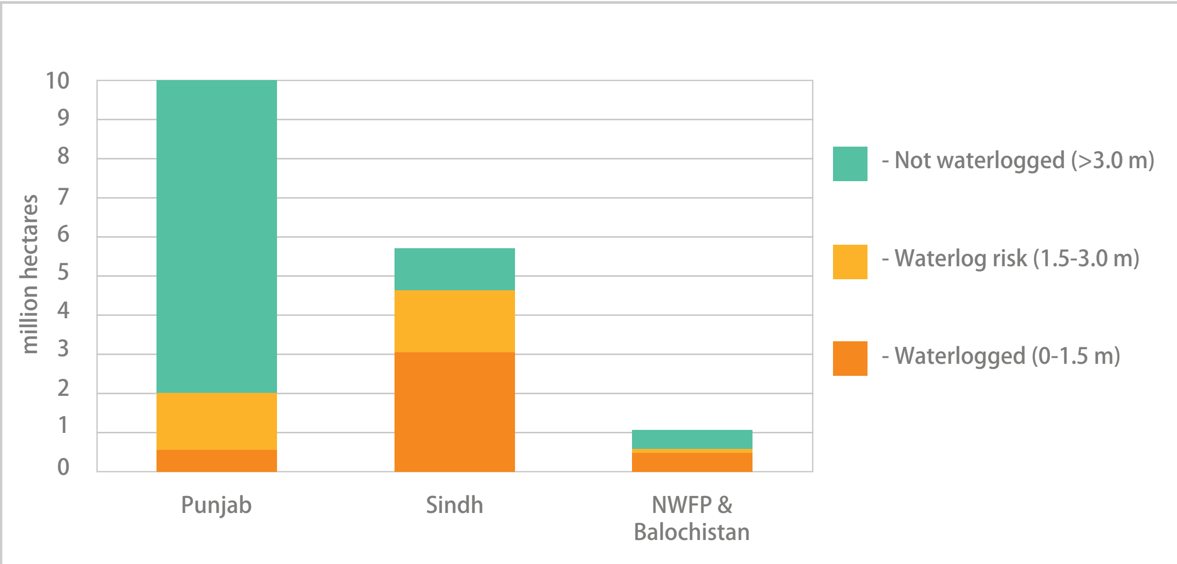

Exhibit 34. Waterlogging status by region of the IBIS irrigation scheme in Pakistan. More than half of the irrigated area of Sindh province is waterlogged, with groundwater depth less than 1.5 metres. (Source: 2006 data from Zaman & Ahmed 2009)

Inadequate soil drainage typically leads to salt accumulation, or salinization. Large-scale irrigated agriculture generally faces the challenge of salinization, because freshwater supply used for irrigation inevitably has some minor salt content. Evapotranspiration during crop growth sends pure water to the atmosphere, leaving salt accumulated in the soil (see Exhibit 35). Repeated year after year in the absence of adequate drainage, this leads to salt build-up and reduced crop yields. The accumulated salt may be sodium chloride (NaCl) producing saline soil, or may be sodium carbonate (Na_2CO_3) producing alkaline soil. Soil can also naturally contain salt, from the origin or weathering of the soil.

Exhibit 35. Estimated flows of salt in the Indus River basin, in units of million tonnes per year. Low salinity water from the Himalayan headwaters, which previously had flowed into the ocean, is now diverted in canals and applied to farmland. Pure water is removed by evapotranspiration, leaving salt accumulation in soil and groundwater. Each year, at least 8 million tonnes of salt accumulate within the Indus basin. (Source: adapted from World Bank 2005)

Soil salinization causes reduced crop yields, and in some cases, forces the abandonment of farmland. Salt-induced land degradation is more common in arid and semiarid regions where rainfall is too low to maintain a regular leaching of salts in the soil through rainfall infiltration. The most-affected regions in South Asia include the Indus Basin in Pakistan and the Indo-Gangetic Basin in India, although the problem exists at smaller scale in other regions of South Asia.

Region-wide assessment of salinization is challenging due to sparsity of information on the subject, and lack of commonly agreed methods to assess the degree of irrigation-induced salinization. It is thought that in Pakistan, about 2 million ha of irrigated land, or 10% of all irrigated land, has been lost from production due to salinization (Aslam & Prathapar 2006). An estimated 28,000 to 40,000 ha per year are lost per year in Pakistan, or 0.14% to 0.20 % of Pakistan's irrigated land per year.

If this trend continues at the same rate, an additional 5% to 7% of Pakistan's irrigated land will be lost by 2050. India is also affected by salinization, and it is estimated that about 9.4 million ha of cropland in India, or about 5% of all arable land, is degraded by saline or alkaline soils (Dagar 2005).

A Pakistani child sleeps on a cot during a prolonged flood.

3.10 Flooding during storms will become more frequent and intense

Due to global climate change, the total average rainfall is projected to increase in South Asia, and is expected to fall in fewer but more intense weather events. Over the long term, precipitation is more likely to come as heavy rainfall (even in regions that receive less total precipitation), leading to increased erosion, landslides and flooding.

Trends in increased intensity of rainfall during recent decades have been documented by Goswami et al. 2006, Dourte et al. 2013, and Singh et al. 2014 (see Exhibit 36). Projections of future extreme precipitation are described by Jayasankar et al. 2015 and Lutz et al. 2016b.

Meanwhile, rapid urbanisation in South Asia has increased physical land cover and thus reduced opportunities for rainwater infiltration, thus increasing the proportion of rainfall that runs off. Furthermore, rapid growth of urban population has led to dense settlements in floodplains and other areas vulnerable to flooding.

In lower areas of many river basins, the number and severity of floods is expected to increase due to more intense storms, greater run-off and higher exposure. Extreme precipitation is also projected to negatively affect water quality, due to increased sediment, nutrient and pollutant loadings caused by heavy rainfall, and disruption of water treatment facilities during floods.

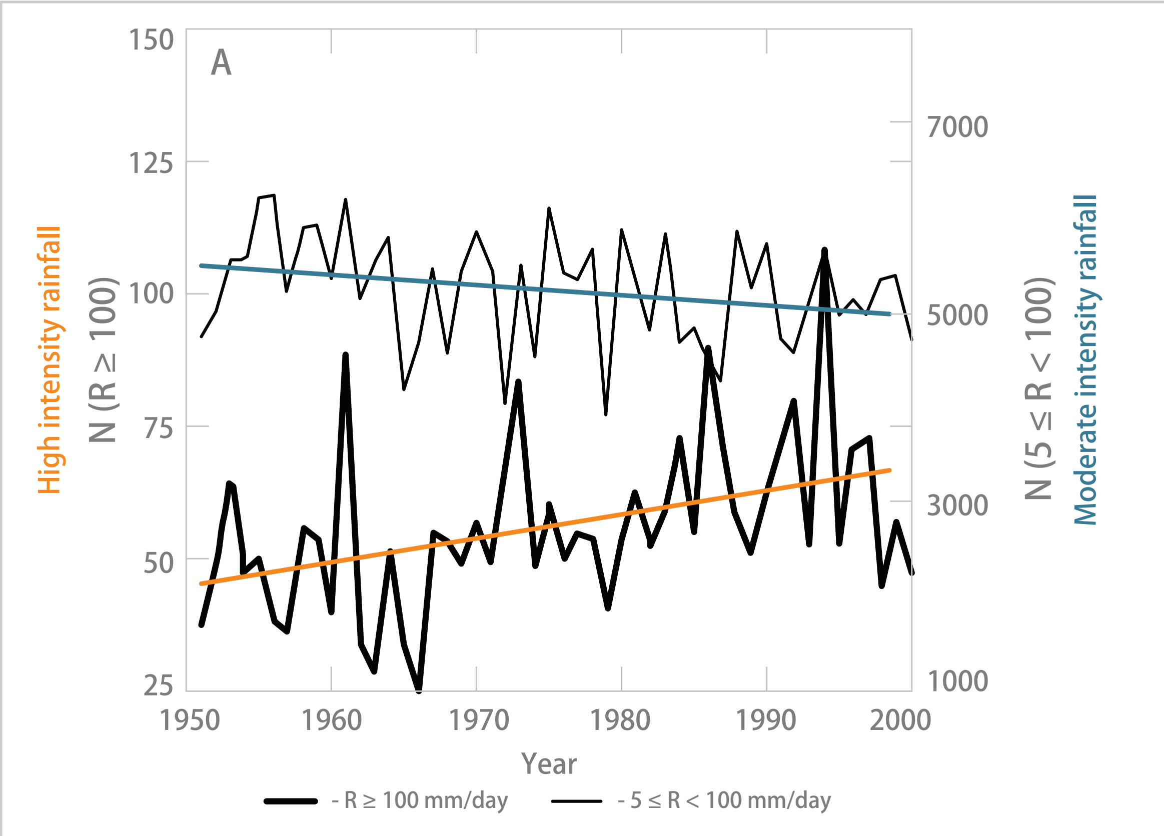

Exhibit 36. Rainfall intensity in South Asia has increased during recent decades, leading to fewer total rainy days, but with heavier rainfall when it comes. This trend is projected to continue and increase due to global climate change. The figure shows rainfall events in central India since 1951; the number of events with heavy rain (greater than 100 mm/day, red line, left scale) is increasing, while the number of events with moderate rain (between 5 and 100 mm/day, blue line, right scale) is decreasing. (Source: adapted from Goswami et al. 2006)

3.11 Glacial melting is permanently altering the Indus River flow

The Himalayan region contains the greatest area of perennial glacial ice in the world outside the polar regions (WCD 2000). These glaciers serve as natural storage reservoirs that provide perennial water supplies to the rivers of the Indo-Ganges-Brahmaputra basins. Glacial melt contributes more than 40% of the total flow of the upper Indus (Lutz et al. 2016a). It is a critical source of water during the summer shoulder seasons (before and after the rains from the summer monsoon), when melt water comprises 70% of the river's summer flow (IBWG 2013).

Climate change is expected to cause long-term alterations to the hydrologic patterns of the Himalayan region, but there is considerable uncertainty about the severity of the changes and the variability between regions (Immerzeel et al. 2010). The Indus River, in particular, is projected to have significant changes to the timing and amount of river flows (Miller et al. 2012). The general expectation has been for increased water flow in the upper Indus River in the coming decades as Himalayan glaciers shrink due to warmer temperatures, but then a permanent reduction of flow after glaciers have largely melted (World Bank 2005b; Rees & Collins 2006) (see Exhibit 37).

However, other changes to the water cycle will also likely be introduced by climate change, such as increased total precipitation (Jayasankar et al. 2015), thus the overall balance of effects is uncertain. Glaciers in most of the Himalayan region are losing mass in response to climate warming, though glaciers in the Karakoram region that feed the Indus River have been expanding in recent years (Bolch et al. 2012; Lutz et al. 2016a).

The reason for this phenomenon – known as the "Karakoram anomaly" – is not yet fully understood, though it may be due to irrigation in the upper Indus leading to greater cloud formation, or to variation in regional atmospheric circulation (Forsythe et al. 2017). Furthermore, trends show a reduction in run-off magnitude and a declining proportion of glacial contribution to the Indus flow, contrary to expectations (Sharif et al. 2013).

There is considerable uncertainty about the timing and severity of climate-induced changes to the Indus River flows, but there is general consensus that the hydrology of the region is quite sensitive to climate variation (Yu et al. 2013). Pakistan thus faces an uncertain future, which may include a short- to medium-term increase in Indus River flow, followed by a longer-term reduction. The temporary increase may be considered a "new normal" rather than a temporary phenomenon, leading to severe water shortages when the Indus River ultimately enters a lower post-glacial flow regime.

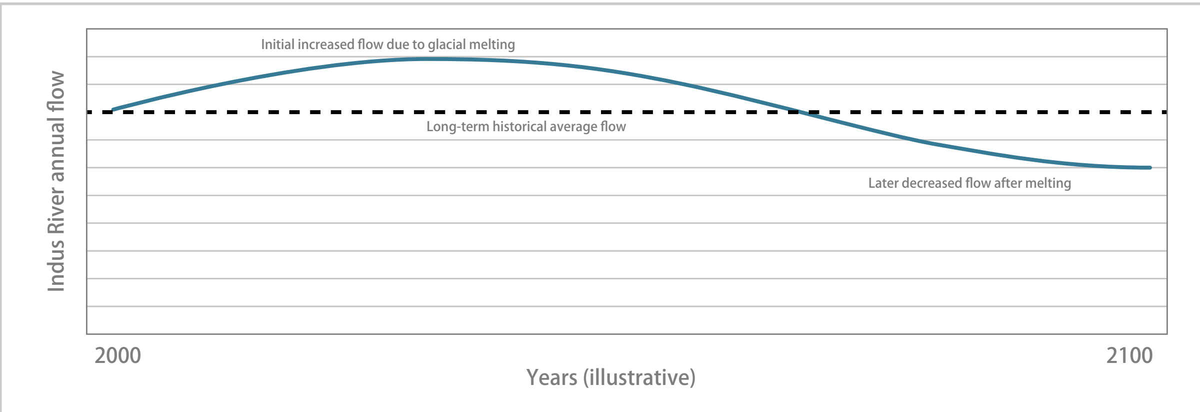

Exhibit 37. Annual average water flow in the upper Indus River is expected to increase in coming decades as Himalayan glaciers melt due to warmer temperatures, but then decrease after glaciers have largely melted. The timing and extent of the change remain highly uncertain, thus the figure is illustrative. (Source: ITT analysis based on World Bank 2005b, Shah 2009, Immerzeel et al. 2010, Miller et al. 2012, Lutz et al. 2016a)

3.12 Lack of means to access local water sources causes economic water scarcity

Economic water scarcity occurs where the lack of human, institutional, and financial capital limits access to water, even though water is available locally in nature to meet human demands. Some places contain abundant water resources, but some segments of the local populations face water scarcity because they lack the means to access it. This may occur in urban and rural areas, and involve drinking, household and irrigation water.

There is a strong relationship between socioeconomic status and access to adequate household water. Globally, India has the largest number of rural people without access to clean drinking water, totalling over 63 million people in 2015. During the same year, there were 13.6 million and 11.6 million people living without access to clean drinking water in Bangladesh and Pakistan, respectively (WaterAid 2017). Exhibit 38 depicts the relationship between income and access to improved water sources in rural Bangladesh and Pakistan: poorer families have lower access to safe water supplies.

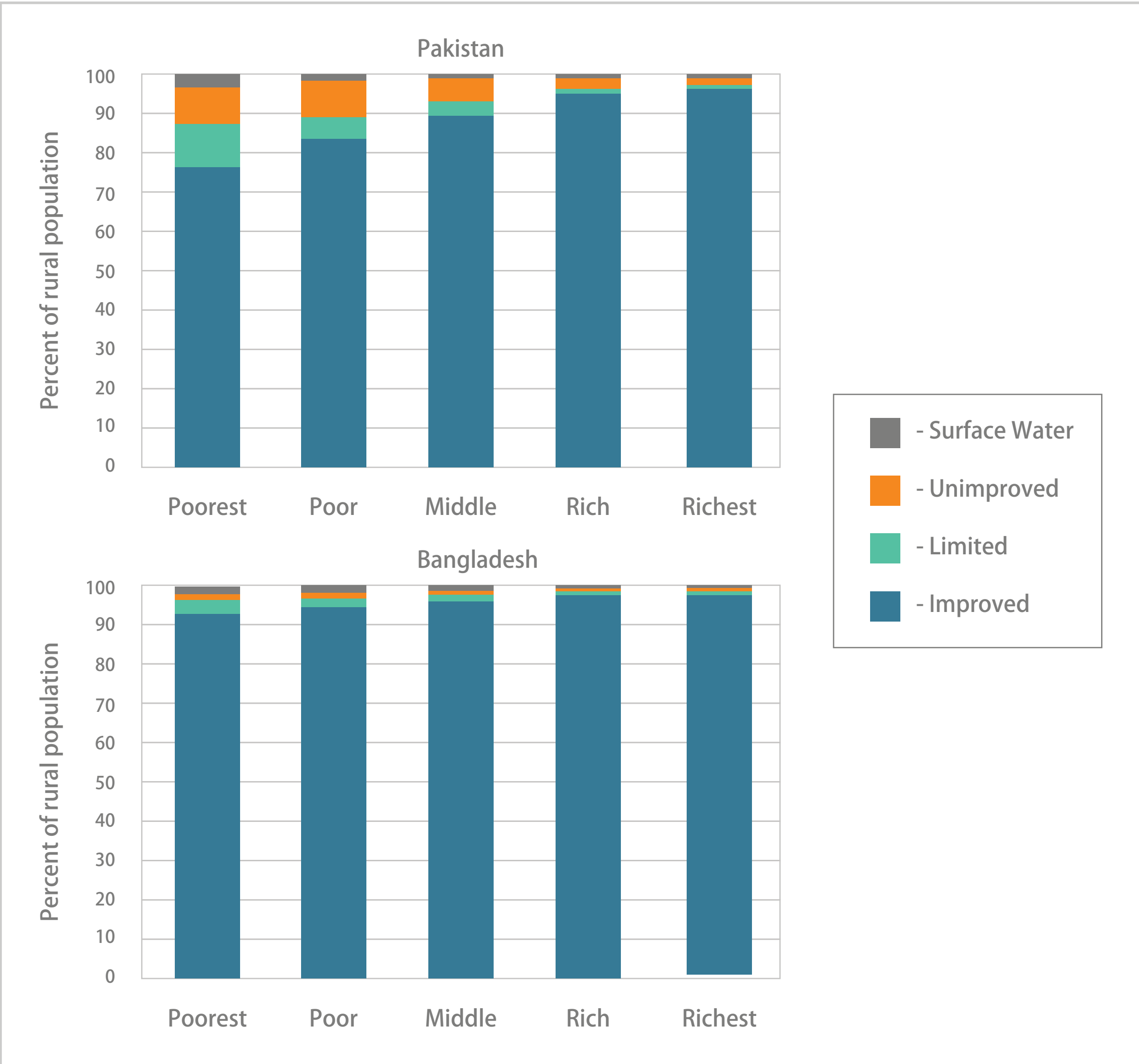

Exhibit 38. Poorer populations tend to have less access to improved household water sources. (Source: year 2013 data from JMP 2017, describing household water sources for socioeconomic quintiles of rural populations of Pakistan and Bangladesh)

Rural populations are at a greater disadvantage in gaining access to drinking water due to their remote locations, weak infrastructure, and lack of public funds. Furthermore, a lack of awareness often prevents people from knowing which sources of water are safe to drink from, and the health implications of consuming contaminated water. Without adequate economic resources, people facing these issues cannot afford to attend school, dig improved wells, or purchase clean drinking water.

Climate change exacerbates these issues since the poorest people bear the brunt of extreme weather events. Bangladesh, India and Pakistan are all extremely vulnerable to climate change, yet least prepared to adapt to the changes (ND-GAIN 2017).

Economic water scarcity for agricultural irrigation is most common in Sub-Saharan Africa, among communities using low-yielding and highly-variable subsistence rain-fed farming methods, despite abundant shallow groundwater. In South Asia, physical water scarcity is more commonly felt by households and farmers, though in specific regions there is abundant unutilised groundwater that could be sustainably used for household consumption and to increase agricultural production and economic prosperity.

Exhibit 39 introduces an index of economic water scarcity for Indian farmers, combining metrics of unirrigated farmland, smallholder farms and unutilised groundwater. In general, north-eastern Indian states suffer most from economic water scarcity for irrigation. An estimated 80 million farmers in India, cultivating roughly 30 million smallholder farms, are affected by economic water scarcity (ITT estimates based on data from the Indian Ministry of Agriculture 2015).

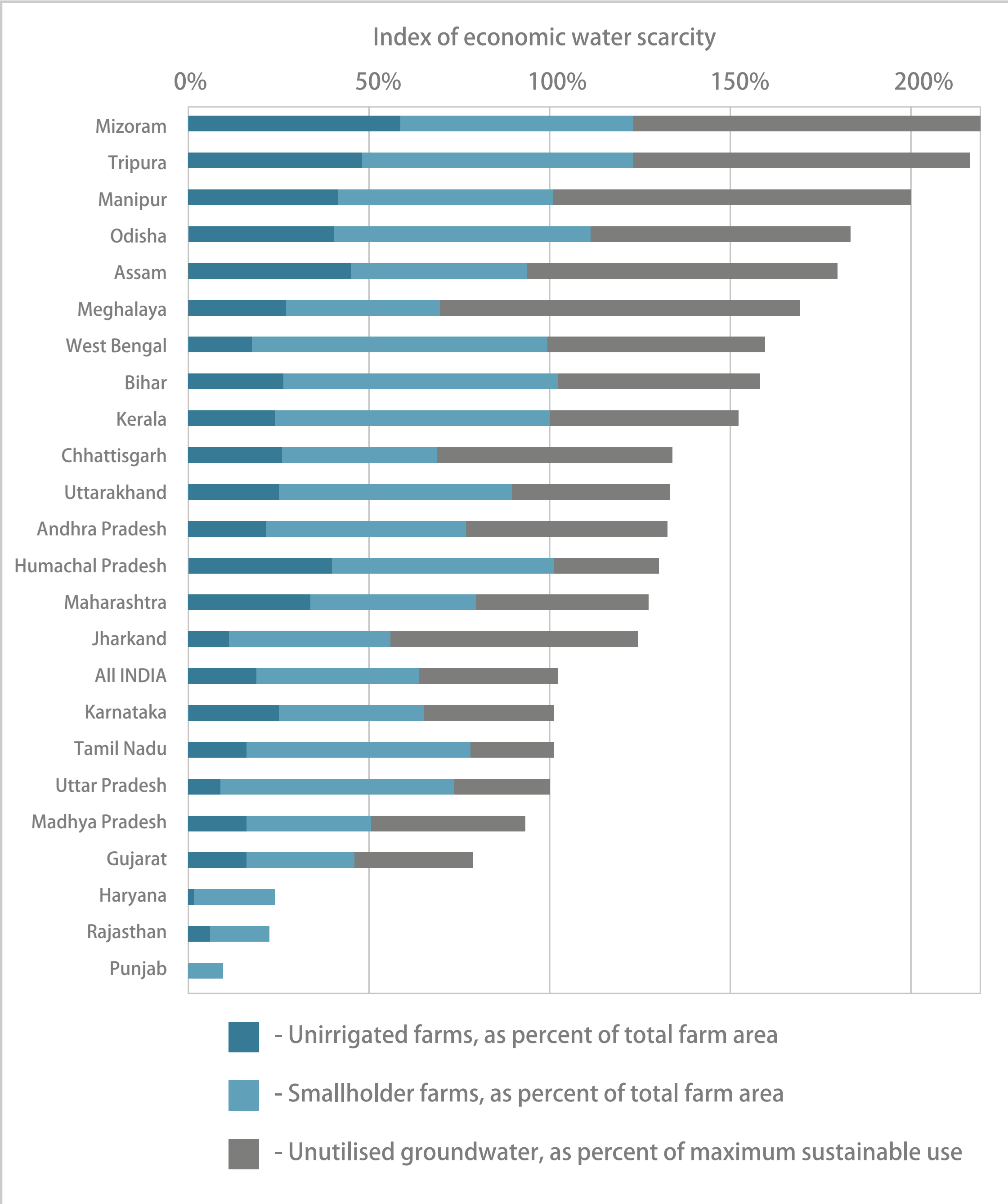

Exhibit 39. Rural economic water scarcity in Indian states is estimated with an index combining unirrigated farmland, smallholder farms and unutilised groundwater. Economic water scarcity is most prevalent in north-eastern India. (Source: ITT analysis based on farm data from India Ministry of Agriculture 2015, and groundwater data from CGWB 2015a)

While traditionally considered a problem of rural communities, there is also a strong urban component of economic water scarcity. Aggregated per capita urban water supply statistics mask the inequity between citizens, with the poorest residents barely securing water for subsistence, while the wealthiest residents enjoy abundant water supply (see Exhibit 40). Poor households may apply a "hierarchy of water needs" (similar in concept to Maslow's hierarchy of needs) and prioritise available water for essential uses (see Exhibit 41). Often living in informal settlements without connections to municipal water supply, poor urban households end up paying elevated retail prices for essential water delivery from private service providers, or risk disease by using contaminated local water sources.

Private markets for drinking water are expanding in cities, serving the communities living in slums as well as the wealthier classes. Expensive bottled water is increasingly used in developing countries, due to the inadequate quantity and quality of piped water supply. Since 2004, consumption of bottled water in low- and medium-income countries has increased by 174%, compared to 26% in high-income countries (Cohen & Ray 2018).

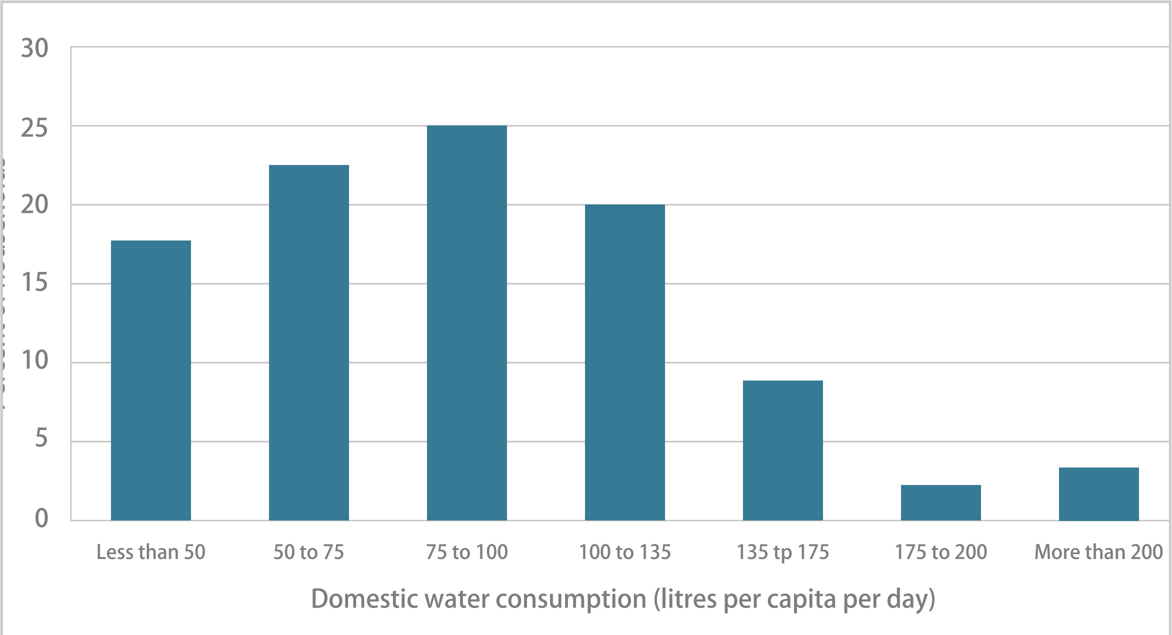

Exhibit 40. Daily water use in urban households varies widely, with 17% of households using less than 50 litres per capita, while 14% of households use more than 135 litres per capita. The average household water consumption is 92 litres per capita per day. (Source: data from Shaban & Sharma 2007, based on survey of seven Indian cities)

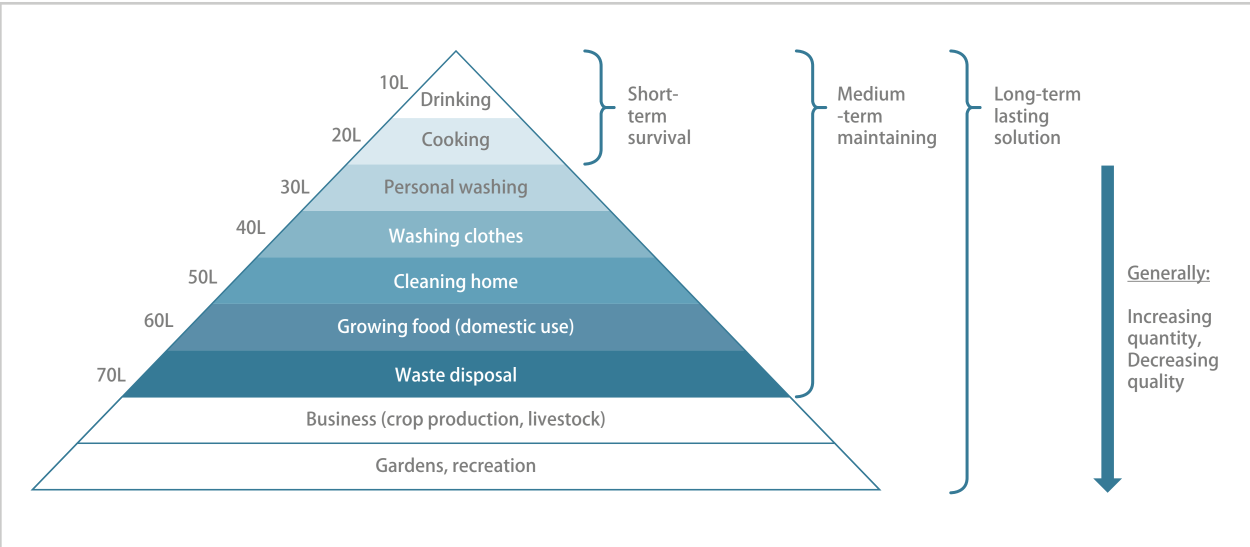

Exhibit 41. Households require access to sufficient water for numerous uses in a hierarchy of water needs. (Source: WHO 2005)

A family in Rajasthan collects water from a hand pump

4. ASSESSING OPPORTUNITIES TO ENHANCE WATER SECURITY

Water security is a complex, multi-faceted issue that may be affected on many fronts including technology innovation and diffusion, organisational and administrative changes, and individual behavioural changes (see Exhibit 42).

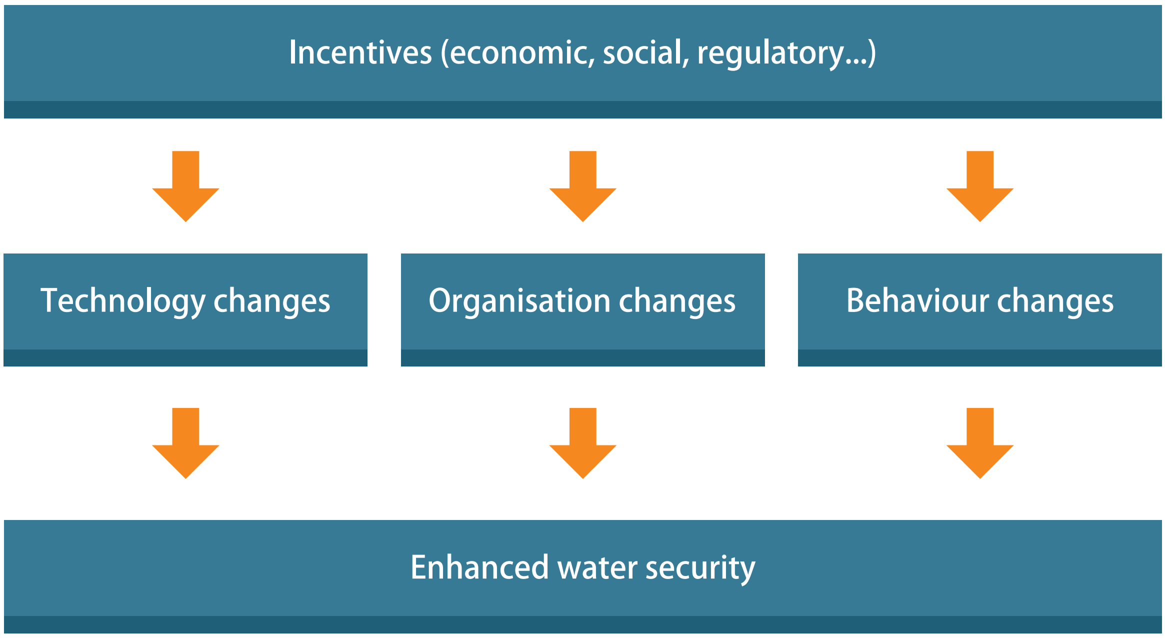

Exhibit 42. Water security may be enhanced through changes of technology, organisation or behaviour, which in turn are caused by social, economic or regulatory incentives.

Broadly speaking, water security interventions may seek any of the following three goals (see Exhibit 43):

- Reducing water demand, by using less water to achieve the same ends
- Increasing water supply, to provide more water to be used
- Integrating multiple aspects of the water system, to increase whole-system efficiency.

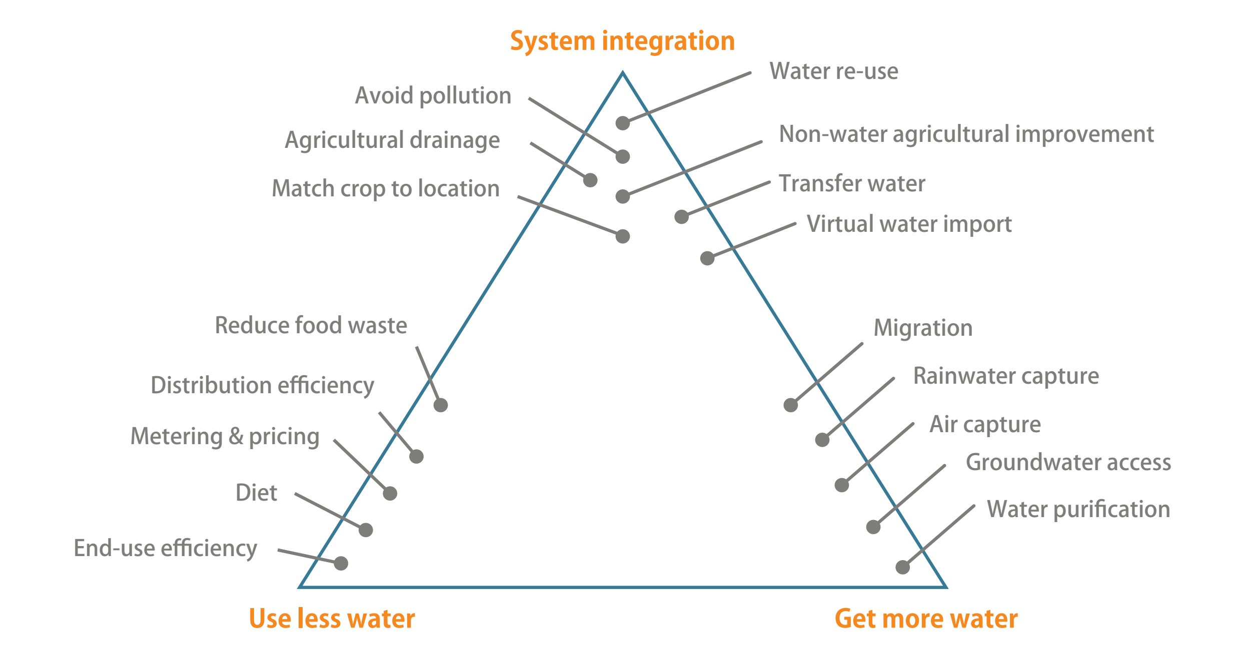

Exhibit 43. Various approaches can be used to enhance water security, which seek to use less water, get more water, and integrate water system processes.

The water cycle is a complex mix of natural and managed processes. Knowledge of the magnitude of various water stocks and flows can help to identify high-potential interventions to enhance water security.

Exhibit 44 comprehensively describes the national-level water balance of India, indicating the annual flows and stocks of water throughout the Indian water cycle. Similar holistic perspectives are important at both larger (regional, global) scales and smaller (basin, city, farm, household) scales.

The perspectives from different scales may give different information and may lead to decisions that are contradictory to one another (Perry 2007; van Halsema & Vincent 2012). For example, decisions made to save water at a household or farm scale perspective, may have adverse effects at the basin scale due to changes in return flow that affect downstream users, ecological services or groundwater recharge.

Exhibit 44. India water balance, circa 2018. Numbers in circles are water flows (km^3 per year), numbers in blue boxes are water stocks (km^3). (Source: see methods and data below)

India water balance: Methods and data

The India water balance in Exhibit 44 is based on the following data sources and methods:

- Precipitation based on 1170 mm annual average precipitation over a surface area of 3,287,263 km^2 (from FAO 2012)
- Groundwater (GW) extraction based on CGWB 2015a, updated based on current trends
- GW recharge based on CGWB 2015a
- Surface water (SW) run-off based on CWC 2015
- SW extraction based largely on Kumar 2005, updated based on current trends
- SW evaporation based on Planning Commission 2009
- Partition of GW and SW into Agriculture, Household and Industry based on Kumar 2005
- Partition of Agriculture water into 75% Evapotranspiration and 25% Return flow
- Partition of Household water into 30% Evapotranspiration and 70% Return flow
- Partition of Industry water into 20% Evapotranspiration and 80% Return flow
- Green water use by agriculture based on Mekonnen and Hoekstra 2011
- Transboundary river water flows to and from India based on FAO 2017b
- Desalinated water quantities based on FAO 2012
- Natural evapotranspiration value determined by mass balance among precipitation, run-off, green water, GW recharge and natural evapotranspiration
- River discharge to ocean value determined by mass balance among rivers from other countries, rivers to other countries, run-off, SW extraction, SW evaporation, return flow and discharge to ocean
- GW flow to ocean value determined by mass balance among GW recharge from rain, GW recharge from return flow, GW extraction and GW flow to ocean. Minimum flow is ~35 km^3/yr based on CGWB 2015a
- SW reservoir live storage capacity based on CWC 2015
- GW storage based on pore volume of upper 200 m of Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal, assuming average water table depth of 10 mbgl and aquifer porosity of 0.15
- Indian Ocean storage based on Eakins & Sharman 2010
- Himalayan glacier storage based on Frey et al. 2014, corresponding to ice volume for the entire Himalayan–Karakoram region
- Atmospheric storage estimated based on global storage of 12,900 km^3 (USGS 2018) assuming atmospheric storage is proportional to surface area

Rice paddy farmers in Bangladesh.

5. NON-TECHNOLOGY LEVERS TO ENHANCE WATER SECURITY

Although the focus of this report is technological levers for water security, here we briefly mention six potentially important levers based on economic, behavioural and geographic changes.

Two non-technology levers aim to use less water:

5.1 Economic incentives and appropriate water pricing

Current water allocation methods in South Asia rarely incentivise efficient use of water. For example, flat electricity tariffs were introduced in India decades ago to encourage more bore wells and electric pumping, and continue to give perverse incentives to farmers to over-exploit groundwater (Mukherji 2017). Adjusting the economic context of water use through suitable water pricing structures and appropriate subsidies would not, by itself, change the physical flow of water. However, it may act as a powerful personal and institutional incentive to adopt water-saving behaviours, processes and technologies. This reflects, ultimately, an appropriate valuation of an increasingly scarce resource (Garrick et al. 2017).

Appropriate valuation of water resources may be the single most important broad strategy to achieve water security. Nevertheless, there is often hesitation among policymakers to enact pricing structures that reflect the full societal cost of obtaining agricultural, household and industrial waters (Water Resources Group 2009). While initially disruptive to water intensive activities, realistic pricing would stimulate efforts to increase water efficiency and decrease waste, leading to improved water security. The specific mechanisms of water savings are manifold (see Section 6), and would be selected by individuals and organisations based on their merits.

In all cases, structures must be in place to protect the absolute need for water of bottom-of-pyramid households who have fewest economic means. Pricing of basic quantities of water out of reach of the poorest populations, or failing to provide public standposts for free water, leads to urban economic water scarcity (see Section 3.12).

5.2 Shift to less water-intensive diet

Production of foods such as cereals, fruits and vegetables typically require less water than foods such as meat, eggs and nuts (see Exhibit 45). Recent trends, globally and in South Asia, are toward higher per capita consumption of water-intensive food products (see Exhibit 6). Shifting societal consumption patterns toward foods with lower water use may be done using pricing, awareness raising, labelling or other incentives (Hoekstra & Chapagain 2007). Food pricing based on real societal costs of production would be beneficial, as water costs are generally not well reflected in the price of products due to subsidies in the water sector.

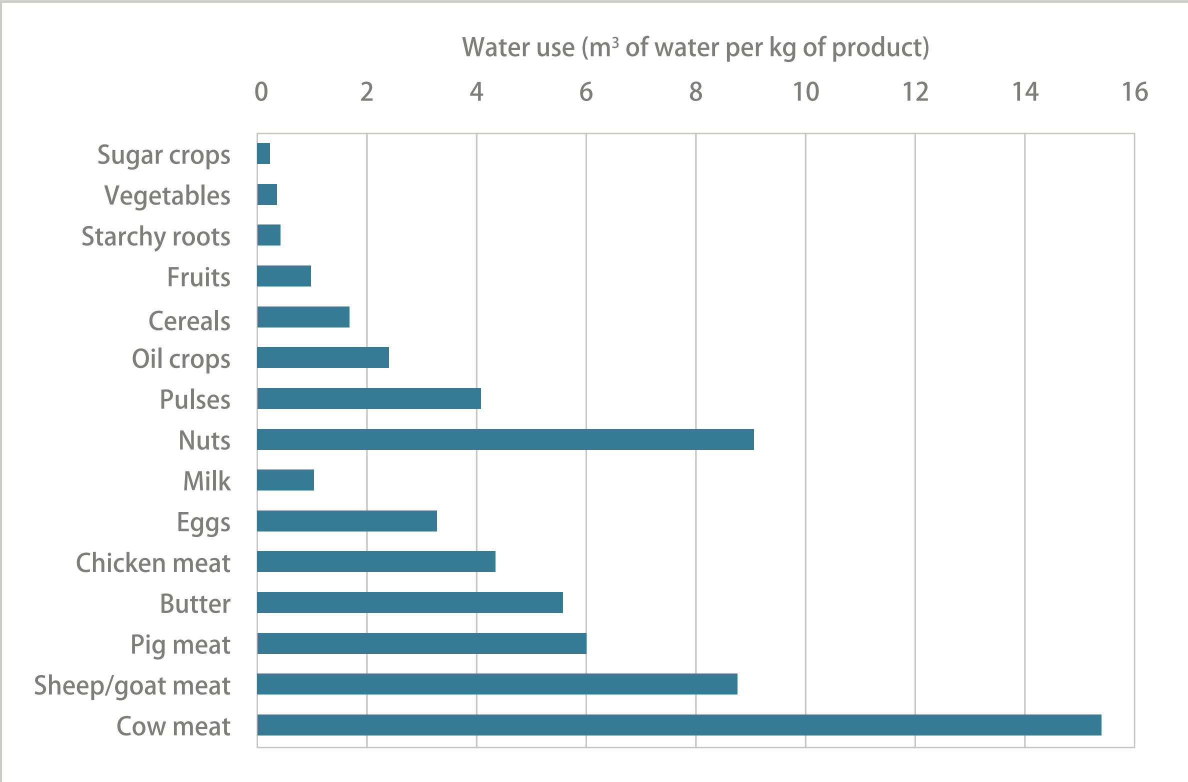

Exhibit 45. Choice of human diet has major impact on agricultural water use, as production of different foods requires vastly different amounts of water. (Source: data from Mekonnen & Hoekstra 2012)

Because South Asia currently has relatively low per capita meat consumption compared to the global average, largely due to cultural and economic reasons, a dietary shift is not likely to further reduce the water intensity of South Asian agriculture (Jalava et al. 2014). Rather, long-term water security benefits would primarily result from maintaining a water-efficient diet and avoiding the addition of more water-intensive foods to the diet.

Two non-technology levers aim to get more water:

5.3 Food trade: virtual water flows

The importation of food, feed and fibre products from more water-abundant regions has long been a livelihood strategy for populations in some water-stressed regions. Bringing water-intensive products from elsewhere avoids the need to use scarce local water for their production. "Virtual water" describes the water used to produce a crop, which then virtually flows with the harvested crop when it is transported elsewhere. Virtual water flow typically takes the form of market-based food trade but also occurs in the form of humanitarian food transfers.

Between countries, import and export of virtual water represents a potential lever for enhancing future global food security, depending strongly on economic factors. National food availability can increase without increasing national water stress by increasing imports or reducing exports of food products. Presently, Australia and several North and South American countries are the greatest exporters of agricultural virtual water, while Japan and several European countries are the greatest importers (see Exhibit 46). South Asian countries are neither strong net importers nor exporters of agricultural virtual water.

In the longer term, net importation of virtual water may expand in South Asia, especially if the industrial and service sectors develop further and gain greater economic leverage. Although self-sufficiency of food supply (especially of cereals) has traditionally been high national priorities in South Asia, this priority may recede in the future if the agricultural sectors represent smaller shares of national economic production.

Dependence on global food markets may prove risky, however, as many other rapidly growing nations also increasingly rely on the same markets. Furthermore, many countries that have abundant water have very little arable land resources and are therefore not able to use the available water for crop production (Kumar & Singh 2005). Relatively few countries have both high arable land availability and total water sufficiency, which are needed to create agricultural surplus and become a virtual water exporting country.

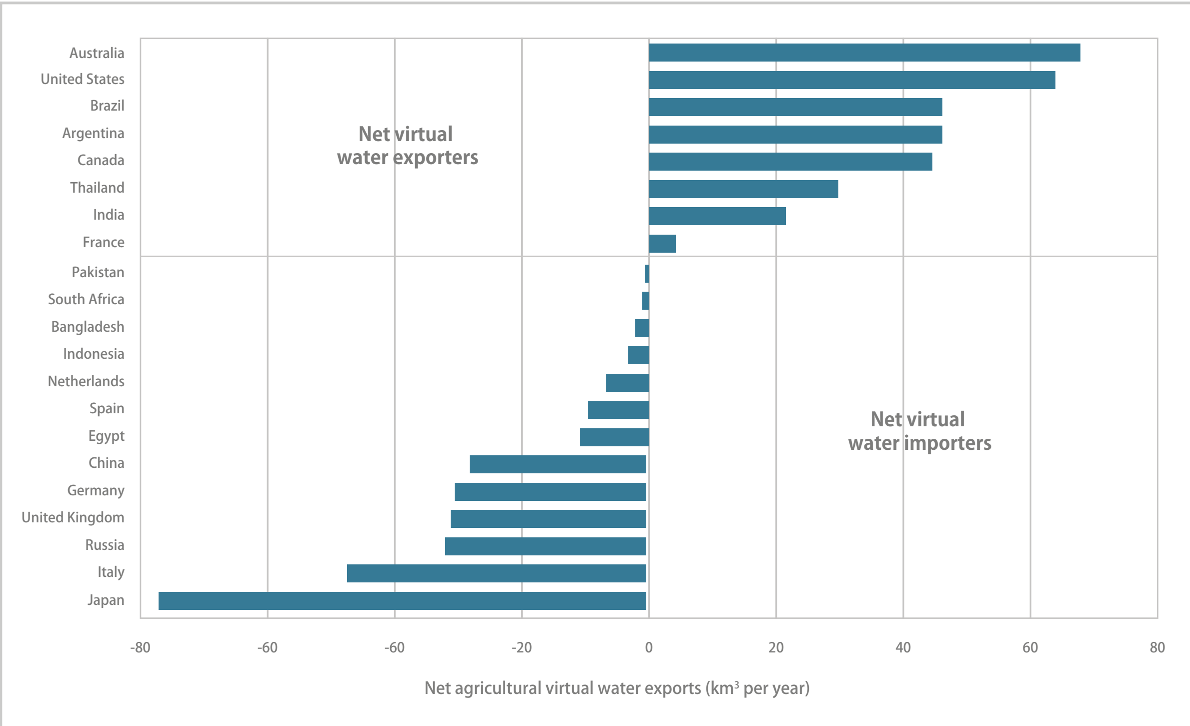

Exhibit 46. Virtual water flows between countries whenever water-intensive commodities such as food, feed and fibre are traded internationally. Major exporters of agricultural virtual water include Australia and North and South American countries. Major importers of virtual water include Japan and several European countries. (Source: year 1997-2001 data from Chapagain & Hoekstra 2008)

Within countries, significant virtual water trade also occurs. Within India, however, virtual water flows from water-scarce regions to water-rich regions. Among Indian states, Punjab exports the most virtual water while Bihar imports the most virtual water (see Exhibit 47). The virtual water exported from Punjab is largely unsustainable groundwater, while Bihar possesses abundant unutilised groundwater resources (see Section 3.3). The reason for this mismatch is that the water-rich regions have relatively little arable land and are unable to fully utilize their abundant water (Kumar et al. 2012). Under such conditions, virtual water trade becomes a solution for land scarcity, and cannot concurrently be used to solve water scarcity.

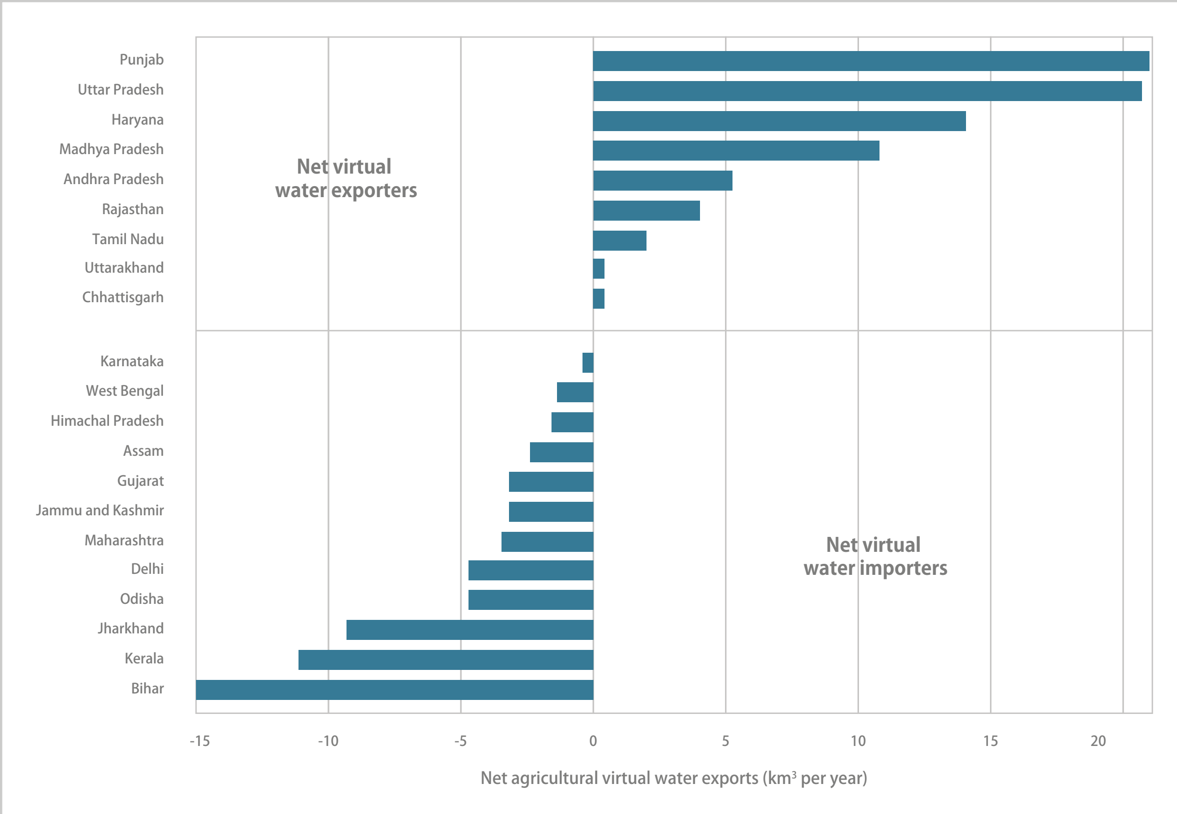

Exhibit 47. Water-intensive agricultural commodities are traded between Indian states and represent flows of virtual water from exporting states to importing states. Among Indian states, Punjab and Uttar Pradesh export the most virtual water, while Bihar and Kerala import most virtual water. (Source: year 1997-2001 data from Kampman 2007)

5.4 Migration from water-scarce regions

The plight of climate refugees is becoming more common around the world, as droughts, floods, rising seas, and other forms of environmental change force people from their homes. Migration to water abundant regions is a last-resort option for many people living in drought-prone areas, but as climate change-induced droughts become protracted, people may have no other choice (Bremner & Hunter 2014, Nazar 2016). Not only is water required to sustain basic human life, but it is a large part of many people's economic livelihoods. During prolonged droughts, nothing can function – schools close, doctors shut down their practices, and farmers can no longer produce food for themselves and the markets (Doshi 2016).

India is the world's largest consumer of groundwater and is extremely vulnerable to the threats of groundwater depletion, especially in arid areas. Migration from these regions to both urban areas and rural areas with more abundant water resources is increasing. Many researchers have attempted to qualitatively and quantitatively measure migration from water-scarce regions, and have found numerous compounding factors.

Fishman et al. (2013) found that, in addition to depleting groundwater resources in an agricultural area, those from wealthier families were more likely to migrate to cities where they had familial or social ties. Sreedhar et al. (2010) concluded that individuals with less formal education were more influenced by push factors, such as water scarcity. Coffey et al. (2015) identified short-term or seasonal migration patterns by lower income groups. These studies illustrate the strong influence that water scarcity can have on migration, and that push and pull factors usually operate simultaneously.

The scale of future water-related migration in South Asia will depend in large part on the success of broader water security measures, as well as the severity of climate change impacts. The governments in South Asia should plan and prepare for such events in the future, to assist in the temporary or permanent relocation of migrants to areas where water is sufficient (Saeed 2015).

People will most likely migrate to urban areas where employment opportunities may exist and there is less dependency on the land. Urban centres should prepare for the expansion of infrastructure and other urban services to assist drought migrants who have no food, money, or jobs (Doshi 2016).

Two non-technology levers aim for greater system integration:

5.5 Match crop to location and water availability

Due to various perverse incentives, water-intensive crops are increasingly grown in water-scarce regions of South Asia. Many agricultural development schemes have exclusively focused on crop productivity and economic goals, while ignoring mounting constraints and concerns about water availability. This has led to production levels of water intensive crops that are untenable in some regions. Two noteworthy examples include sugarcane production in the Indian state of Maharashtra, and rice production in Punjab state.

Sugarcane is a water intensive crop, requiring a year-round water supply. In Maharashtra, despite 45% of the state being considered drought-prone, 26 out of 36 districts grow sugarcane (Government of India 2017). Sugarcane cultivation has increased rapidly in Maharashtra during the past two decades (see Exhibit 48), and the state is now one of the leading sugar producers in India. Sugarcane cultivation utilises 71% of all irrigation water in Maharashtra (India Ministry of Agriculture 2013).

In some areas, despite the lack of water, sugarcane cropping has continued with use of private water tankers. Sugarcane production has brought economic benefits to Maharashtra, but its disproportionately high use of water has limited the expansion of irrigated cultivation of other food crops in the state.

Rice planting

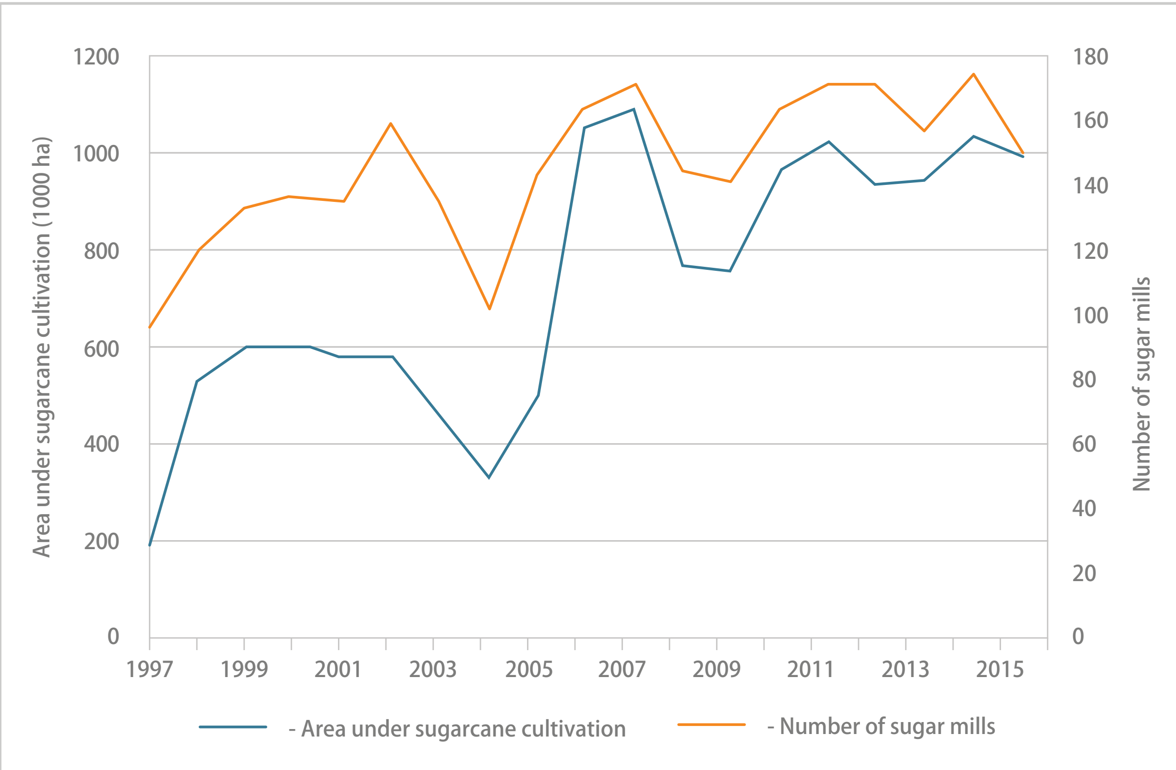

Exhibit 48. The area under sugarcane cultivation in Maharashtra state has increased fivefold in the past two decades, and the number of sugar mills has increased. This cultivation has required vast amounts of water, utilising over 70% of all irrigation water in the state. (Source: sugarcane area data from India Ministry of Agriculture 2013, 2015; sugar mill data from Maharashtra Sugar Federation 2008, Pawar & Zodage 2015, Maharashtra Sugar Commissionerate 2017)

Prior to the Green Revolution, farmers in Indian Punjab grew a variety of crops, including wheat, pulses and coarse cereals. Since the 1960s, agriculture in Punjab has changed greatly and is now dominated by winter wheat and summer rice cultivation (see Exhibit 49). This cropping pattern requires very large amounts of water, which in Punjab has been increasingly provided by groundwater. This has been the primary cause of the alluvial groundwater depletion described in Section 3.3.

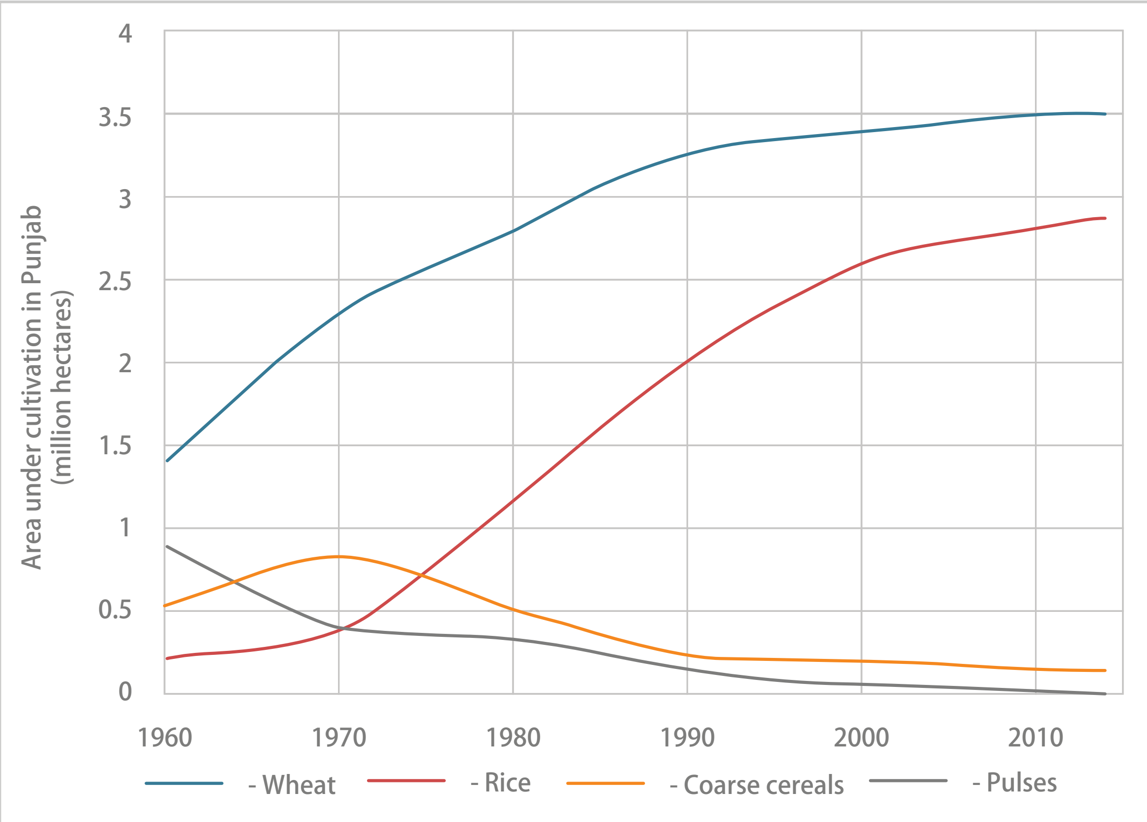

Exhibit 49. Since the 1960s, agriculture in Indian Punjab has transitioned from a mixed cropping pattern including wheat, pulses and coarse cereals, to a cropping pattern dominated by winter wheat and summer rice cultivation. This has led to vastly increased water consumption. (Source: 1960-61 to 2010-11 data from UNEP 2013; 2014-15 data from India Ministry of Agriculture 2015)

Although entrenched interests will support the continuation of these unsustainable forms of water use, long-term resolution of water security challenges in South Asia will require a shift in cropping patterns that favour water-intensive crops in water-abundant regions, and water-conserving crops in water-scarce regions (Davis et al. 2017).

5.6 Reduce food waste to reduce crop production requiring use of water

Currently, a non-trivial portion of the total food production is wasted, either on the farm, during transport and storage, or in the household. If that wastage were reduced, fewer crops would need to be produced, thus less water would be used. Jha et al. (2015) estimated that about 5 to 15 percent of most crops in India are lost during harvest or post-harvest (see Exhibit 50). In general, dry crops such as cereals and pulses suffer less loss, while fresh crops such as fruits and vegetables have greater levels of loss.

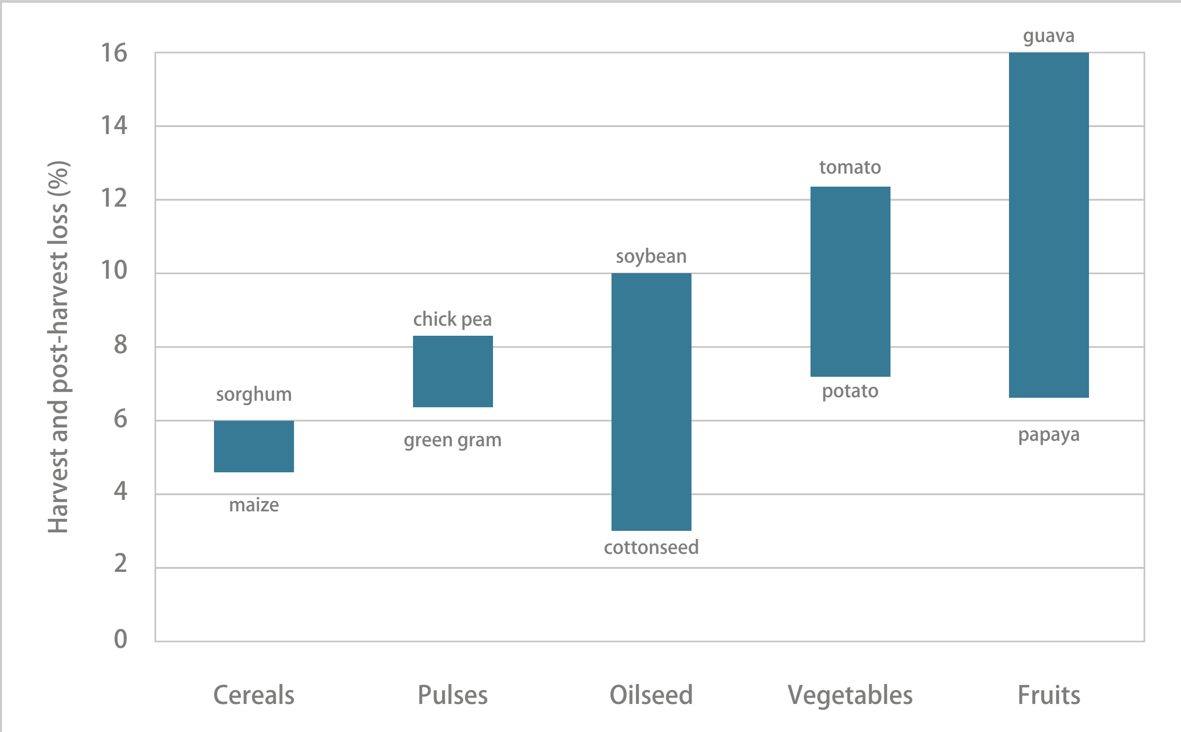

Exhibit 50. Roughly 5 to 15 percent of most Indian crops are lost during harvest or post-harvest. (Source: data from Jha et al. 2015)

Crop losses occur during harvest due to farm-level technical and managerial issues, and spoilage during processing and distribution is largely a function of the available infrastructure (Lundquist et al. 2008). Anecdotal evidence suggests that losses at the household and consumer levels are minimal in South Asia. Approaches to reducing food waste may involve technological innovation and diffusion, for example refrigeration systems to reduce food spoilage at farms, distribution chains and households. We do not consider these technologies in this report, because their effect on water security is indirect.

6. TECHNOLOGY LEVERS TO ENHANCE WATER SECURITY

A wide range of technology interventions are available to improve water security in South Asia, seeking to reduce water demand by using less water to achieve the same ends, increase water supply to provide more water to be used, and integrate multiple aspects of the water system to increase whole-system efficiency. These are summarised in Table 4 and described in detail in this Section.

Use less water	6.1 Improve end-use efficiency	6.1.1 Irrigation water-use efficiency improvements
		6.1.2 Domestic water-use efficiency improvements
		6.1.3 Industrial water-use efficiency improvements
	6.2 Improve conveyance efficiency	6.2.1 Urban water distribution efficiency
		6.2.2 Irrigation water conveyance efficiency
	6.3 Metering for management and billing	
Get more water	6.4 Capture and store rainwater	6.4.1 Small-scale rainwater harvesting and storage
		6.4.2 Large-scale surface water storage
		6.4.3 Managed aquifer recharging
		6.4.4 Atmospheric water capture
	6.5 Purify contaminated water	6.5.1 Remove salt from water
		6.5.2 Kill biological pathogens
		6.5.3 Remove arsenic and fluoride from water
		6.5.4 Remove chemical contaminants
	6.6 Identify, access and extract groundwater	6.6.1 Groundwater mapping
		6.6.2 Well drilling
		6.6.3 Water pumping
System integration	6.7 Eliminate pollution sources	6.7.1 Faecal waste management
		6.7.2 Industrial effluent management
		6.7.3 Agricultural run-off management
		6.7.4 Manage saline groundwater intrusion
	6.8 Reuse and recycle water	6.8.1 Greywater reuse
		6.8.2 Large-scale water treatment and reuse
	6.9 Inter-basin water transference	
	6.10 Drainage management	6.10.1 Sub-surface drainage
		6.10.2 Surface drainage
	6.11 Improve non-water agricultural factors	6.11.1 Irrigated farming improvements
		6.11.2 Rainfed farming improvements

Table 4. A range of technology levers can be employed to reduce water use, increase water supply, and improve system-wide integration. The numbers refer to the sections of this report.

Several technology levers aim to reduce water demand, by using less water to achieve the same ends:

6.1 Improve end-use efficiency

6.1.1 Irrigation water-use efficiency improvement

Irrigation in the agricultural sector is, by far, the largest user of water in South Asia, accounting for at least 85% of all water withdrawals in South Asia (see Exhibit 51). Irrigation is an important component of South Asian agriculture, and roughly half of all farmland in South Asia is irrigated (see Table 5).

A borewell in Punjab.

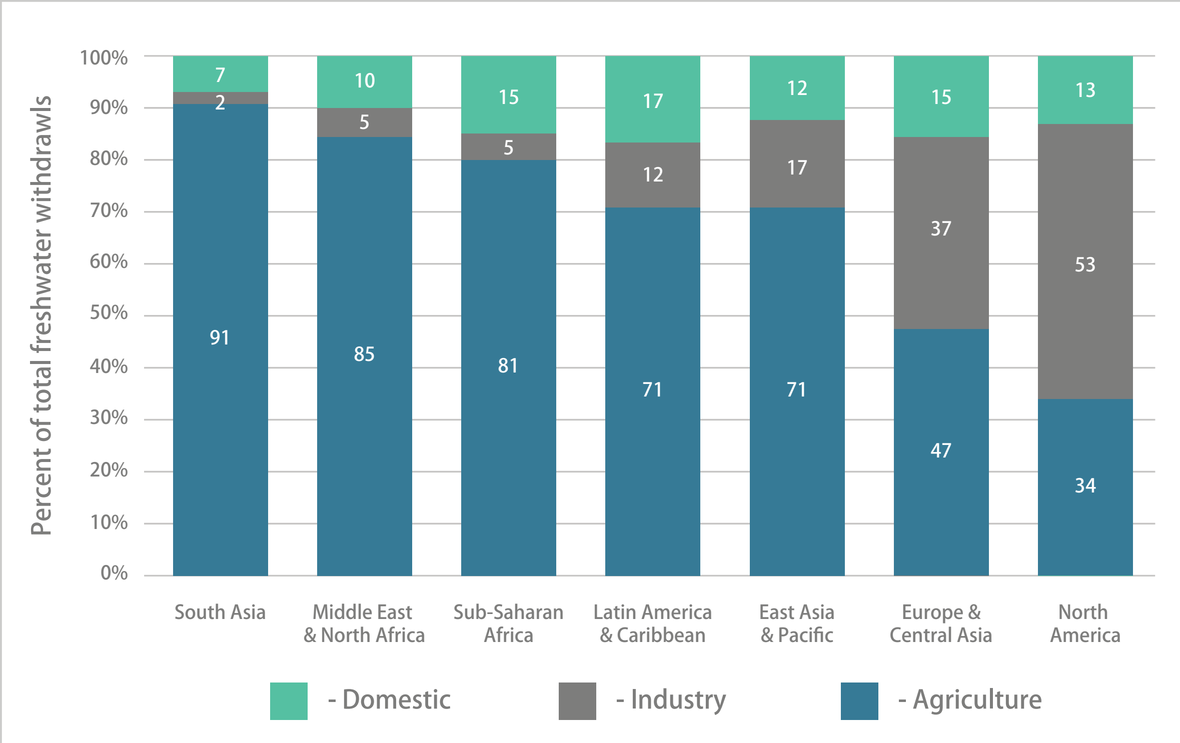

Exhibit 51. The agricultural sector is, by far, the dominant user of water in South Asia. Other global regions withdraw proportionally less water for agriculture and more for household and industrial uses. (Source: 2014 data from World Bank 2017)

Characteristic	Unit	Bangladesh	India	Pakistan
Total land area	thousand km²	130	2973	771
Agricultural land area	thousand km²	91	1796	363
Total land that is agricultural	percent	70%	60%	47%
Per capita agricultural land	ha per person	0.06	0.14	0.19
Area equipped for irrigation	thousand km²	51	704	193
Agricultural land that is irrigated	percent	56%	39%	53%
Per capita irrigated land	ha/person	0.03	0.05	0.10

Table 5. Characteristics of agricultural resources in Bangladesh, India and Pakistan. Well over half of the total land area in South Asia is used for agriculture, and almost half of the agricultural land is equipped for irrigation. (Source: Total and agricultural land areas from World Bank 2017, area equipped for full-control irrigation from FAO 2017c, and per capita values calculated based on 2017 population estimates from UN 2017)

The predominant method of irrigation in South Asia is surface irrigation, in which water flows by gravity across the surface of the field. In South Asia, surface irrigation accounts for 97.7% of the area under full control irrigation methods (i.e. not including spate or flood recession irrigation) (FAO 2011). Localised irrigation including sprinkler and drip methods account for just over 0.1% of the irrigated area.

The most common form of surface irrigation in South Asia is border irrigation, where water is applied to rectangular strips of the field. The sides of the strip are edged with a small ridge or dike. Water is introduced at one end and progressively covers the entire strip. A large volume of water is applied to the relatively flat field surface in a short period of time. A slightly more efficient form of surface irrigation, furrow irrigation, is less common in South Asia. This method uses long narrow channels to convey water across the field, separated by ridges or beds upon which crops are grown.

Surface irrigation techniques are relatively simple, but are among the least efficient of irrigation methods (FAO 1989). Less than half of the applied water is typically transpired by the growing crops, and a small percentage is lost to non-productive evaporation. The remaining water infiltrates into deeper soil layers and becomes groundwater that can be recycled by wells.

Crops get water from two important sources: "green water" that is received directly from rainfall, and "blue water" that is supplied to fields through engineered irrigation structures such as canals and wells. Only a part of the extracted blue water is actually used (i.e. transpired) by the crops--the rest is lost from the field through evaporation and infiltration. The amounts of green and blue water used in South Asia vary widely by crop types, depending on several factors:

- Some crops (such as rice and sugarcane) naturally demand more water than others
- Production quantities and cultivated areas vary widely between crops, led by rice and wheat cultivation
- Some crops (such as pulses and oilseeds) are typically grown on rainfed farms, while others (such as wheat and rice) are usually irrigated
- The conveyance and application efficiencies of irrigation water use vary widely based on technology and management.

Indian agricultural water use is summarised in Exhibit 52, which distinguishes between rainwater that is transpired by the crop (green water), irrigation water that is used (i.e. transpired) by the crop, and irrigation water that is lost from the field through percolation or evaporation.

The single largest user of irrigation water in India is rice cultivation, followed by wheat and sugarcane. Applied irrigation water is the sum of irrigation water that is transpired by the crop and irrigation water that is lost from the field. A large percent of applied irrigation water is lost from the field, mainly through infiltration into deeper soil. Rice accounts for about 45% of all applied irrigation water in India, and wheat accounts for about 23% (see Exhibit 53).

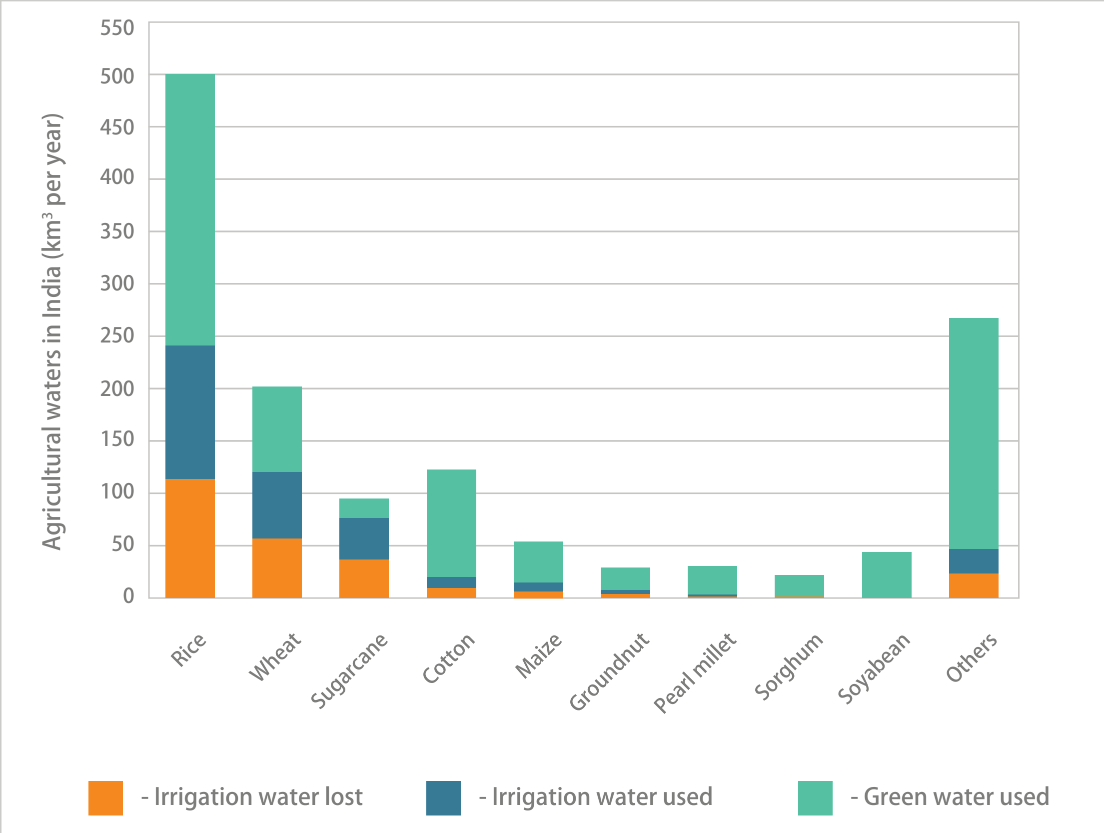

Exhibit 52. Breakdown of Indian agricultural water use by crop (km³ per year). Applied irrigation water is divided into irrigation water that is transpired by the crop, and irrigation water that is lost from the field through percolation or evaporation. Green water is rainwater that is transpired by the crop. (Source: ITT analysis based on annual crop production data from India Ministry of Agriculture 2016, crop water intensity data from Hoekstra & Chapagain 2007 and Mekonnen & Hoekstra 2011, irrigation water application levels from Fishman et al. 2015, and total green water used and total irrigation water applied from Exhibit 44)

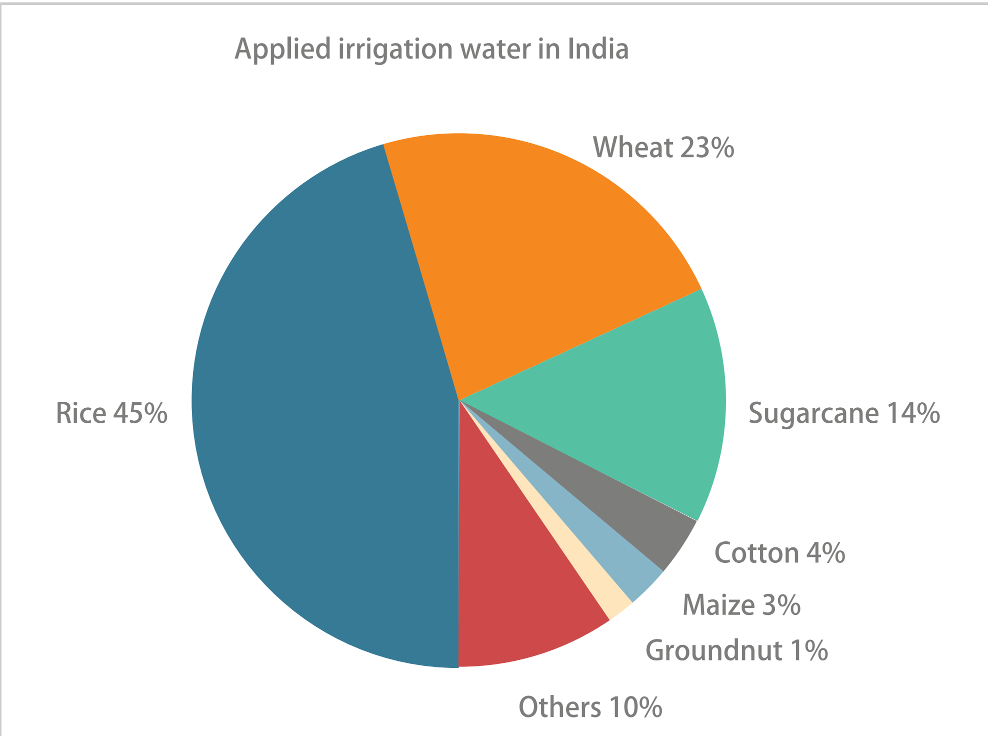

Exhibit 53. Applied irrigation water for selected crops in India, as a percentage of total applied irrigation water. (Source: ITT analysis; see previous exhibit)

Irrigation water use can be made more efficient by reducing the amount of non-productive water loss. Evaporative losses from the soil surface are relatively small, except in the case of row crops such as cotton, castor, ground nut, maize, and some vegetable and horticultural crops. Infiltration of water into the deep soil is a loss from the field, but is still present within the basin. If the infiltrated water flows into a river or a freshwater aquifer, it may be extracted and used by cities or other farmers (Perry 2007). On the other hand, the water is not recoverable if it flows to the sea or into a saline aquifer. Depending on field-level and basin-level hydrological conditions, improved irrigation techniques may reduce the amount of water that is withdrawn and applied to the field, but may not reduce overall water consumption (FAO 2017a, Grafton et al. 2018).

There are large differences between Indian states in both water use efficiency and land use efficiency of rice production (see Exhibit 54), largely because of climatic differences such as precipitation and solar radiation. Punjab, for example, has the highest land use efficiency (usually termed "yield", expressed in units of kg of grain per ha of farmland per crop season), but the lowest water use efficiency (expressed in units of g of grain per m^3 of irrigation water applied). West Bengal, on the other hand, has the highest water use efficiency but mid-level land use efficiency. Irrigation water use efficiency is a function of location (wetter regions typically require less irrigation water per harvest) as well as management and technology (implementation of water-conserving farming practices). Regarding location, we observed in Section 5.5 that long-term water security in South Asia will likely require a more rational geographic distribution of cropping that takes agro-climate into account, with water-intensive crops grown primarily in water-abundant regions. In all locations, however, there is scope for improving both land use efficiency and irrigation water use efficiency through a range of best-practice farm management and technology options.

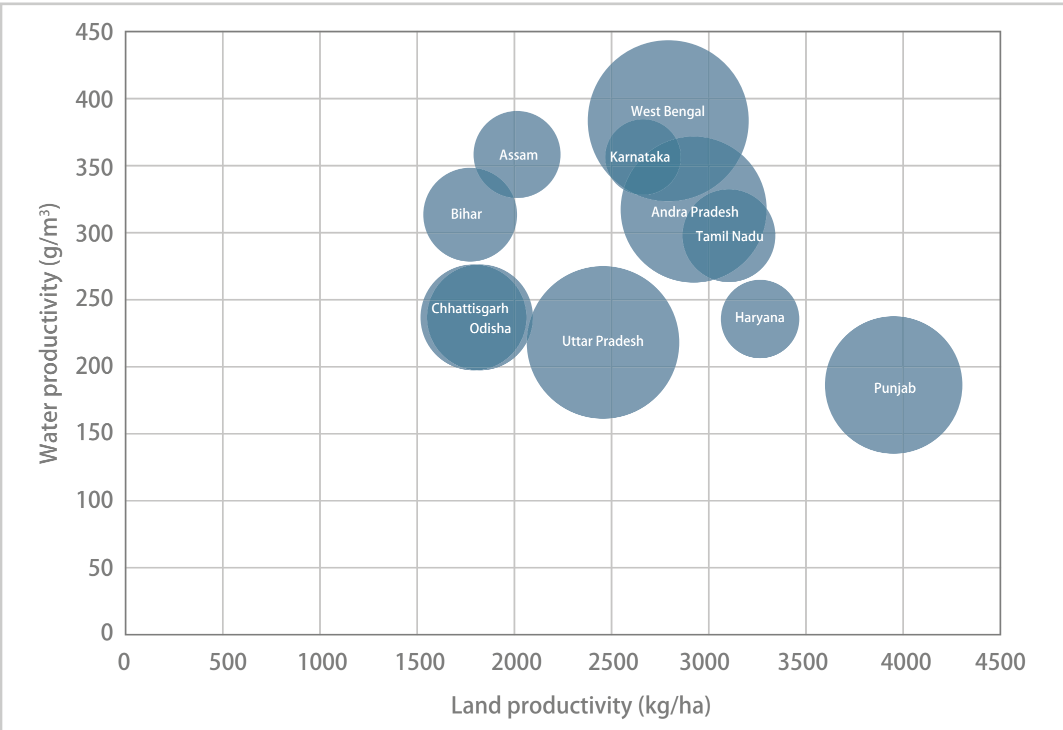

Exhibit 54. Rice production in Indian states varies widely in terms of land productivity (horizontal axis, kg of rice per ha of land) and water productivity (vertical axis, grams of rice per m^3 of applied irrigation water). The size of the circle corresponds to rice production amounts. (Source: ITT analysis based on 2013-14 rice yield and production data from India Ministry of Agriculture 2015, and 2013-14 water productivity data from CACP 2015)

A range of existing technologies and methods can be used to increase water use efficiency in irrigation, with varying costs (see Exhibit 55). Two particularly promising options for improving surface irrigation are precision land levelling and tensiometer-based irrigation scheduling. Two important alternatives to surface irrigation are sprinkler irrigation and drip irrigation.

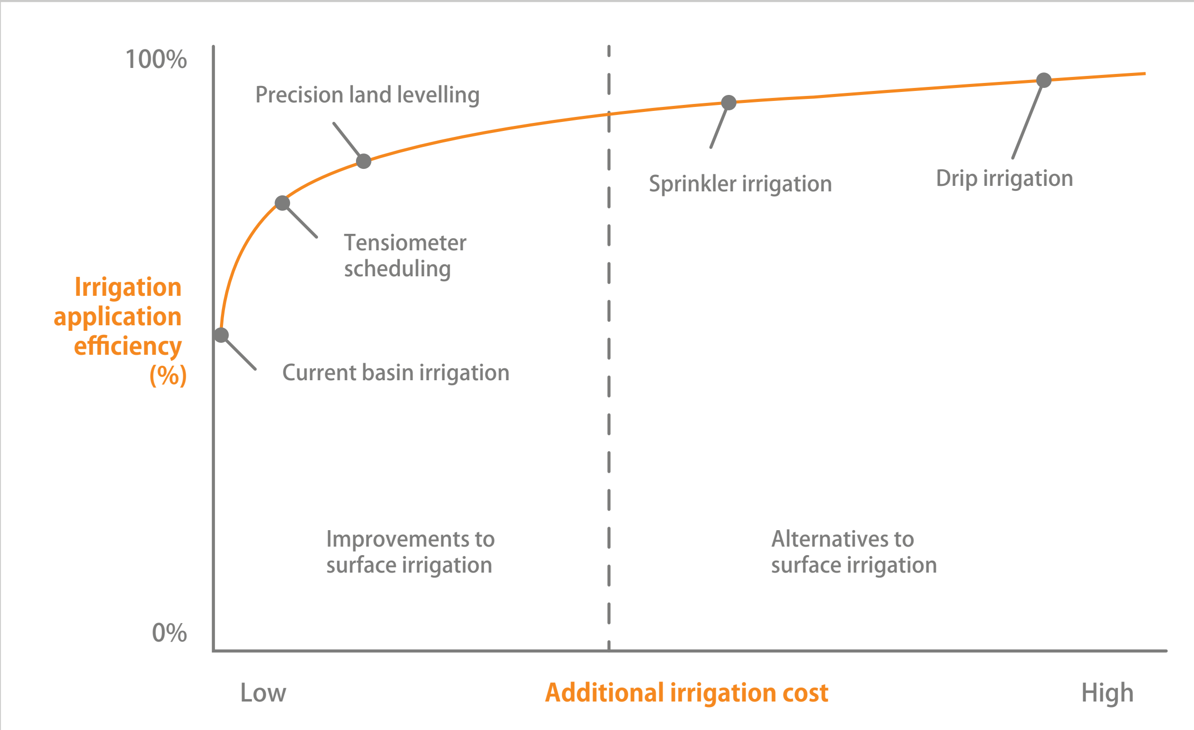

Exhibit 55. Irrigation application efficiency can be increased by various technological means. Application efficiency is defined as the ratio between the irrigation water transpired by the crop, and the water delivered to the field or farm. (Source: ITT analysis)

Precision land levelling (PLL) is a mechanical process of grading and smoothing a farm field to a precise and uniform plane surface with a variation of ±2 cm. This is done with a tractor-mounted device guided by a fixed laser beam to ensure a level surface (see Exhibit 56). The process takes several hours per hectare, and must be repeated every 3-4 years.

Unevenness of the soil surface has a significant impact on seed germination, weed burden, and uneven crop maturing, particularly for rice but also for other crops as well (Aryal et al. 2015). Land levelling increases both water use efficiency and yield of crops (Aggarwal et al. 2010), and is increasingly being adopted by farmers growing rice and wheat (Jat et al. 2015). Implementation of laser land levelling is increasing rapidly in both Pakistan and India, primarily due to its productivity gains and economic returns, but also improving water security by reducing irrigation water needs.

Tensiometers are devices that measure soil moisture. Accurate knowledge of moisture levels in farm fields allows farmers to schedule applications of irrigation water, to ensure that growing crops always have enough, but not too much, water (Bhatt et al. 2016). A low-cost, easy to use tensiometer has been developed by Punjab Agricultural University in cooperation with Columbia University, which can reduce water use in rice production by about 30% (Columbia Water Center 2012). Hard-to-read dials were replaced by simple, colour-coded indicators, calibrated to each crop (see Exhibit 56).

Exhibit 56. Several existing technologies have the potential to significantly reduce irrigation water application in South Asian agriculture. On left, a laser land leveller being used on a farm in Haryana, India. On right, a tensiometer installed in a rice field in Haryana, India. (Source: see Section 10, Photography References)

Another emerging practice for reducing water use in rice cultivation is the System for Rice Intensification (SRI), initially developed in Madagascar in the 1980s. SRI involves a number of practices such as earlier transplantation of seedlings, transplanting single seedlings with wider spacing, use of manure or other organic fertilisers, and intermittent flooding and draining rather than continuous saturation of fields (WWF 2007).

While potentially promising in terms of increased yields and reduced irrigation water use, there remain questions about SRI's effect on total factor productivity (Berkhout et al. 2015), as well as socioeconomic impacts within farming communities (Gathorne-Hardy et al. 2016).

In addition to improving the efficiency of surface irrigation, there are other localised irrigation technologies such as sprinklers and drip irrigators that offer alternatives to surface irrigation. These technologies are increasingly used for higher-value crops, not just for water savings but for increased control and production (see Exhibit 57).

Cultivated area under drip irrigation in India has grown from 7 km^2 in 1992, to 25 km^2 in 1998, to 190 km^2 in 2010, up to 337 km^2 in 2015 (Narayanamoorthy 2016; Grant Thornton 2016). Technical improvements in drip irrigation systems have the potential to significantly reduce the cost and energy use of high efficiency irrigation (Shamshery et al. 2017)

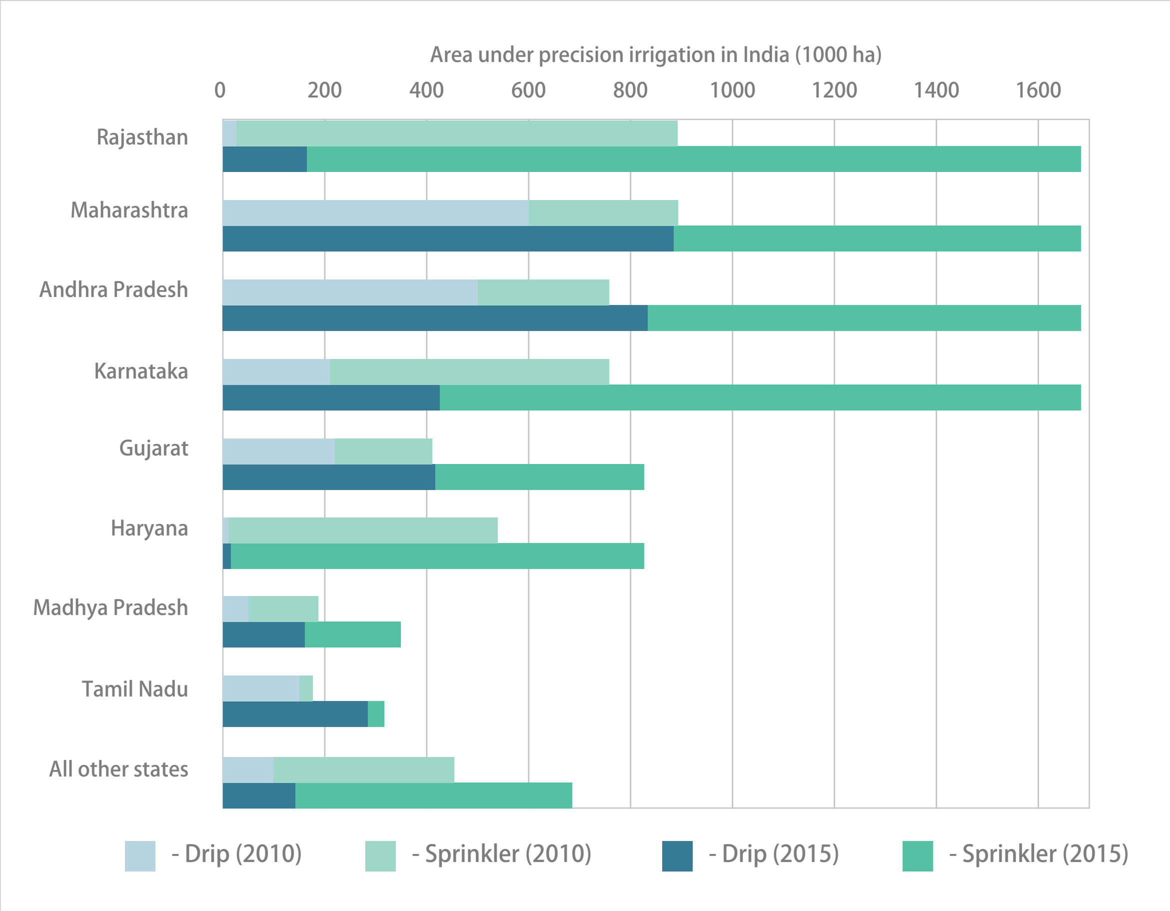

Exhibit 57. Localised irrigation methods are increasingly used in India. Sprinkler irrigation is most commonly used in the states of Rajasthan and Haryana. Drip irrigation is most commonly used in Maharashtra and Andhra Pradesh states. (Source: year 2010 data from Kumar 2016; year 2015 data from Grant Thornton 2016, ICFA 2017)

If existing technologies for irrigation water use efficiency were widely adopted in South Asia, significant reductions in water extraction could be obtained. Within India, the amount of applied irrigation water could be reduced by about 100 km^3 per year through the use of improved irrigation techniques.[8] The net water savings will depend on farm- and basin-level characteristics including water evaporation, sub-surface drainage, and farm expansion (Grafton et al. 2018).

In addition to changes in physical irrigation technology, a new generation of gene editing techniques has the potential to enable the development of novel crop varieties with enhanced resistance to drought and salinity stresses, allowing continued expansion of agricultural production despite growing environmental challenges.

Agriculture in South Asia will face numerous stressors during the coming decades, such as droughts due to climate change, salinization of farmland and groundwater, and basin-level limits to water supply. Conventional plant breeding techniques are hard-pressed to develop crop varieties to accommodate such rapid changes.

[8] This assumes that average irrigation application efficiency increases from 50% to 70%.

Genome editing techniques are capable of precisely and site-specifically (rather than randomly) adding, modifying or deleting genes from plant and animal genomes. Genome editing methods include clustered regularly interspersed short palindromic repeats (CRISPR), zinc-finger nucleases (ZFNs), and transcription activator-like effector nucleases (TALENs) systems.

The CRISPR/Cas9 system, in particular, is proving to have many beneficial uses such as increasing crop yield, improving drought tolerance, increasing growth in nutrient-limited conditions, and breeding crops with improved nutritional properties (Barrangou & Doudna 2016). In this system, the Cas9 nuclease is complexed with a synthetic guide RNA and is delivered into a cell. It then cuts the cell's genome at a desired location, allowing existing genes to be removed and/or new genes to be added.

CRISPR/Cas9 techniques have successfully been used to create variants of maize that have higher grain yield under water stress conditions and have no yield loss under well-watered conditions, compared to conventional maize types (Shi et al. 2016). Varieties with tolerance to salinity are also expected. CRISPR technology may enable crops that use water more efficiently, producing more biomass per unit of water transpired, to increase total agricultural production in regions facing hard limits to basin-level water supply, such as hard-rock regions with closed river basins (i.e. much of peninsular India).

An important part of South Asian agriculture does not use irrigation, and instead depends on rainfall for its water needs. While expanding the use of irrigation is possible in some areas, irrigation is constrained in many regions by lack of water sources or excessive economic costs. Using CRISPR technology to make better use of the "green water" that falls on dryland farms, total agricultural production can increase without the need to harness additional water sources.

Importantly, gene editing with CRISPR is a cisgenic rather than transgenic modification, meaning that genes are artificially transferred between organisms that could otherwise be conventionally bred (Moradpour & Abdullah 2017). Many consider cisgenic editing to be less controversial than transgenic modification, because the edited organisms could, in principle, have been created through conventional breeding.

For this reason, both regulatory procedures (Sprink et al. 2016) and consumer acceptance (Delwaide et al. 2015) are proving to be less challenging for cisgenic editing than for transgenic modification. Of more important concern may be the asymmetric economic relationship between the producers and planters of edited seeds, as genetically modified organisms have typically been produced and marketed by large multi-national corporations. Structures should ensure that improved seeds are available to all farmers in need, to avoid further widening social inequalities.

6.1.2 Domestic water-use efficiency improvement

Domestic water is used by households for drinking, cooking, bathing, washing, toilet flushing, etc. Surveys show Indian households use about 90 to 100 litres of domestic water per person per day, on average (Shaban & Sharman 2007; Singh & Turkiya 2013). By comparison, domestic per capita water consumption in European households average about 130 litres per day (UK Environment Agency 2008). Among rural South Asian households, the dominant water uses are clothes washing, bathing and house cleaning, while urban households used most water for bathing, toilet flushing and clothes washing (see Exhibit 58).

A woman in Jaipur uses water sparingly to wash clothes.

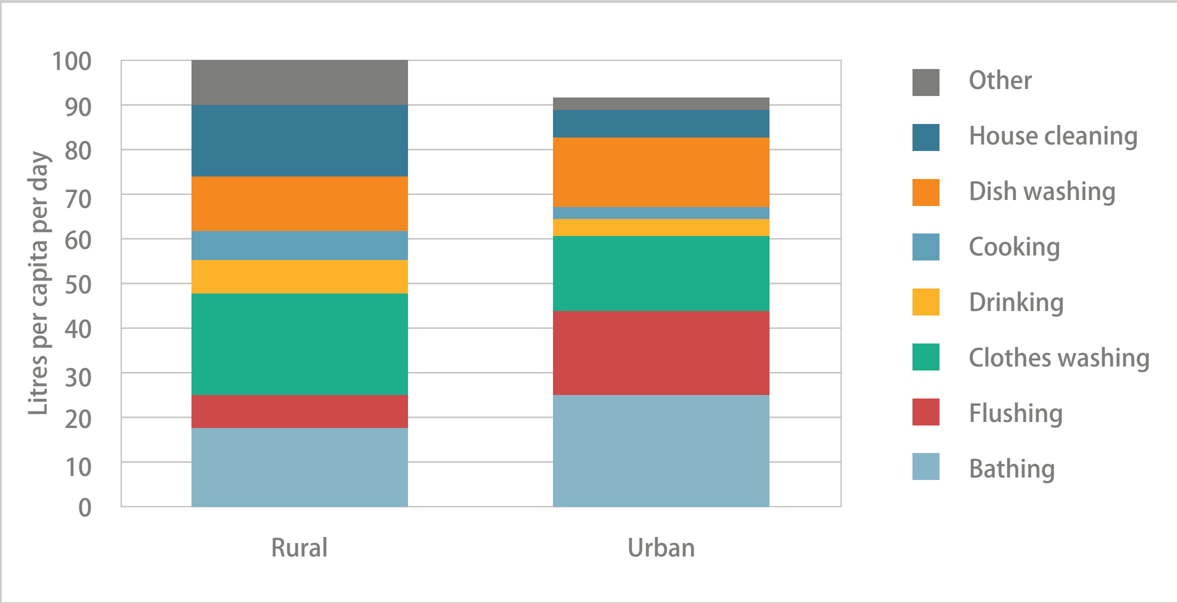

Exhibit 58. Breakdown of water use for different domestic activities, for rural and urban dwellers. (Source: urban data is average of 7 Indian cities from Shaban & Sharman 2007; rural data on village in Haryana, India from Singh & Turkiya 2013)

Household appliances are commercially available that use less water than conventional appliances that perform the same function. These water efficient devices are gaining increasing attention in some industrialised regions facing water constraints. Examples include low flush toilets, low flow sinks and showers, and water efficient clothes washing machines.

In the current South Asian context, water conserving flush toilets may play a role in conserving water, through replacing older flush mechanisms in existing buildings and installing high efficiency flush toilets in new construction. Adoption of low-flow toilets in 80% of Indian urban households could reduce total water withdrawal by 1.2 km^3 per year. Little household water use reduction can likely be achieved through more efficient showers or washing machines in the South Asian context. There is an unknown potential for reducing water loss from household leaks, e.g. leaky faucets and toilets. Global best practice on plumbing maintenance should be applied.

6.1.3 Industrial water-use efficiency improvement

Industrial production in South Asia is increasing rapidly. Many industrial processes require water for various purposes such as cooling and washing. About 68% of total industrial water usage in India is for cooling of thermo-electric power plants (Accenture 2016). A range of methods can be used for power plant cooling, with a large variation in specific water use (see Table 6).

In India, 80% of thermal power generation uses freshwater recirculating cooling systems (WRI 2018) (see Exhibit 59), which have the highest rate of evaporative freshwater consumption of all cooling system types. Other major industrial water users include steel, textiles, pulp and paper. For most of these industries, evaporative consumption is relatively low, with perhaps 80% of withdrawn water returned as wastewater. The wastewater quality from these industries is typically poor, with diverse organic and inorganic contaminants that vary by industry (see Section 3.6).

Cooling technology	Advantages	Disadvantages
Once-through	• Low evaporative consumption • High cooling efficiency • Lowest capital cost • Mature technology	• Highest water withdrawal • Ecosystem impacts from withdrawal and discharge • Restrictions on hot water discharge
Wet recirculating	• Lower water withdrawal than once-through • Mature technology	• Highest evaporative consumption • Lower power plant efficiency than once-through • Higher capital cost than once-through
Dry recirculating	• Very low water withdrawal • No evaporative consumption	• Highest capital cost • Low power plant efficiency (when weather is hot) • Large land area requirement
Hybrid	• Lower capital cost than dry cooling • Less evaporative consumption than wet recirculating cooling • Flexibility in operation	• Higher capital cost than wet recirculating • Limited technology experience

Table 6. Thermal power plants can use various types of cooling systems, which each have advantages and disadvantages in terms of water withdrawal, water consumption, cost, generation efficiency and other factors. (Source: adapted from O'Hagan & Maulbetsch 2009, Mielke et al. 2010, IEA 2012, CEA 2012)

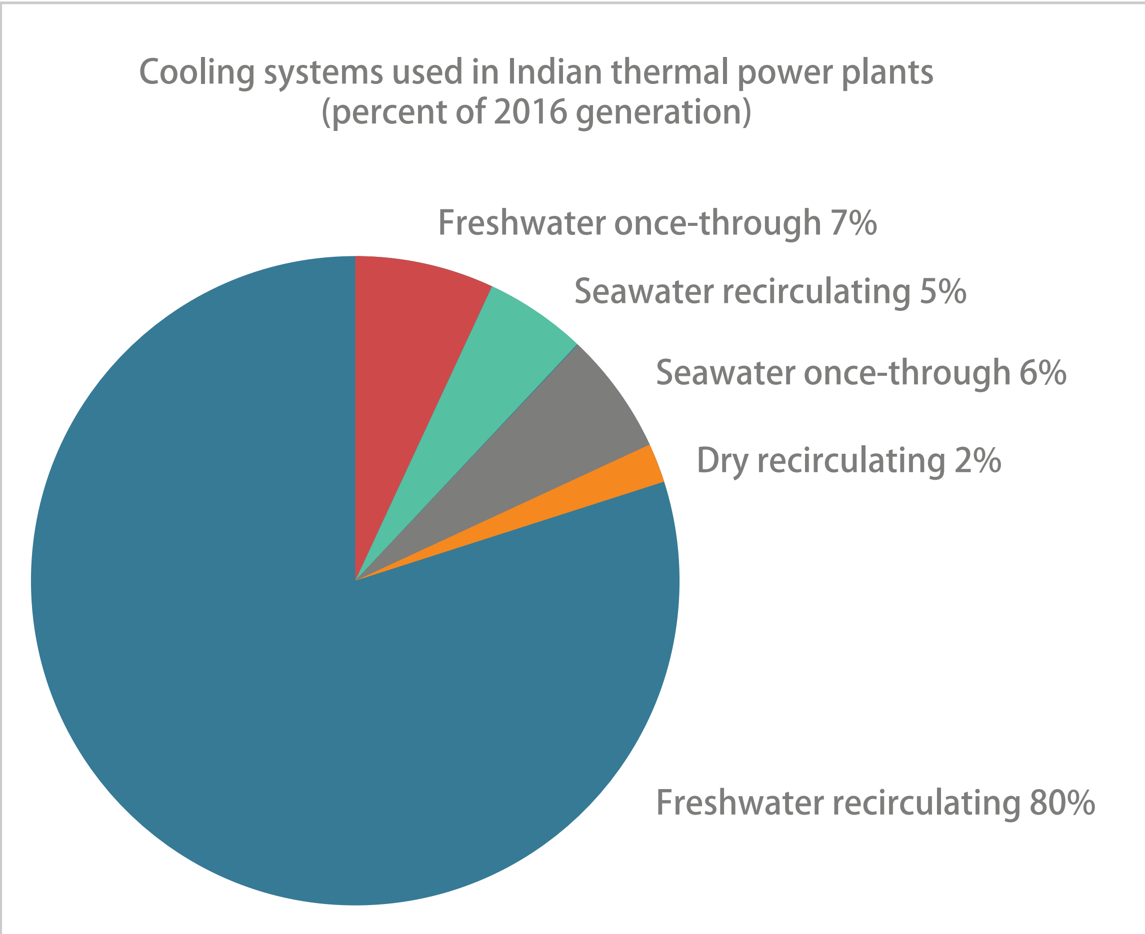

Exhibit 59. Most thermal power plants in India use freshwater recirculating cooling systems, with high rates of evaporative water consumption. (Source: data from WRI 2018)

Current water use efficiency in South Asian industries is typically very low, and the adoption of global best practices would significantly reduce industrial water use (see Exhibit 60). For example, coal-based thermal power plants in India have an average specific water consumption of about 4.5 m^3/MWh, more than twice that used in power plants in other global regions (Accenture 2016). We estimate that adoption of water-conserving measures for power plant cooling in India could reduce water withdrawals by over 20 km^3 per year.[9]

A further example is the steel industry in South Asia, which typically use much more water to produce a tonne of steel than global average (see Exhibit 60). There are ample opportunities to reduce industrial water use in the steel and other sectors, e.g. dry cooling, dry coke quenching, seawater cooling, zero liquid discharge (CWC 2014).

In recent decades, as water constraints have been felt in various parts of the world, much effort has been expended globally to devise industrial processes that conserve water. Implementation of this global best practice in South Asia could significantly reduce future demand for industrial water, and could reduce the quantity and improve the quality of industrial wastewaters. We estimate that adoption of best-practice water conservation measures in the Indian industrial sector (not including power plant cooling) could reduce water withdrawals by almost 10 km^3 per year.[10]

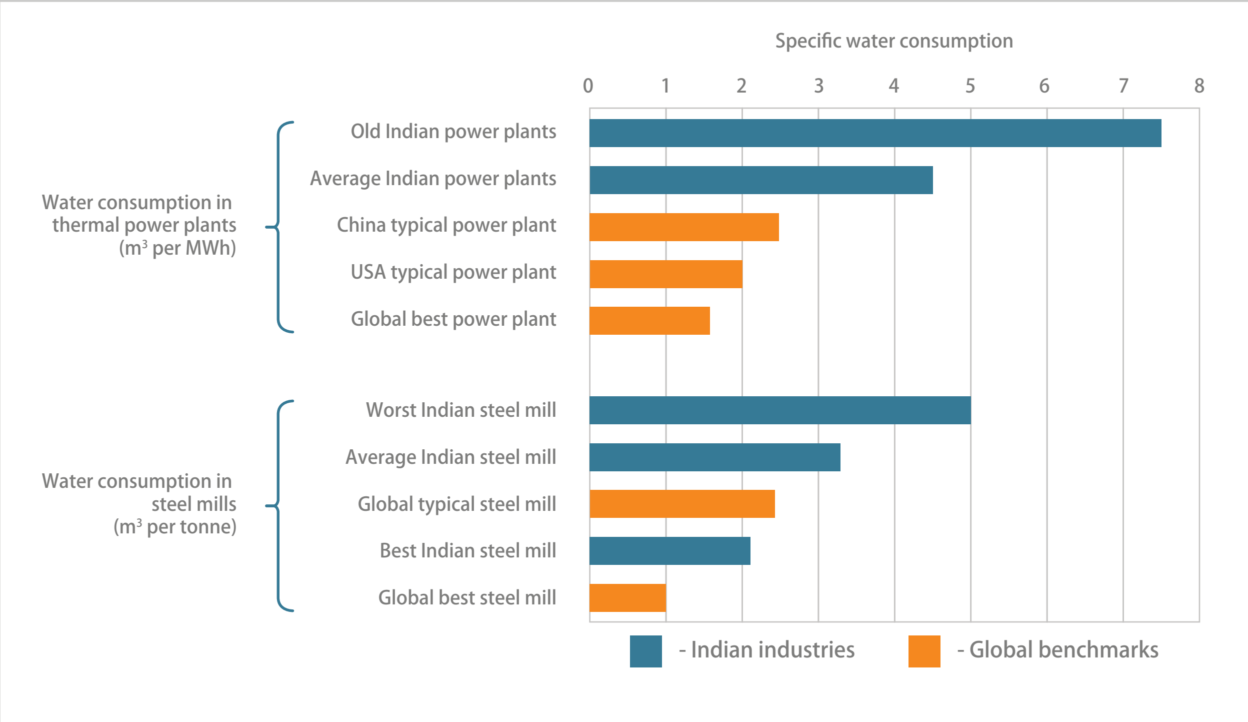

Exhibit 60. There are significant opportunities for South Asian industries to reduce water use by adopting global best practices. Figure shows water use in Indian thermo-electric power plants (top) and Indian steel mills (bottom), compared to international benchmarks. (Source: data from Accenture 2016)

[9]This assumes adoption of water efficiency technologies that reduce specific water use by 50%, in 80% of Indian thermal power plants.
[10]This assumes adoption of water efficiency technologies that reduce specific water use by 50%, by 80% of Indian industries.

While increasing industrial water use efficiency will be critical for enhancing overall water security in South Asia, the electric power sector faces additional water-related challenges. South Asia increasingly faces constraints to electricity generation linked to water availability (IEA 2015).

For example, cooling water shortages in summer of 2010 forced the Chandrapur coal-fired power station in Maharashtra to shut down, leading to power outages across the state. A delayed monsoon in India in 2012 raised electricity demand for pumping groundwater for irrigation while reducing hydropower generation, contributing to widespread sustained blackouts. Between 2013 and 2016, fourteen of India's largest thermal power utility companies experienced disruptions at least once due to water shortages (WRI 2018).

6.2 Improve conveyance efficiency

6.2.1 Urban water distribution efficiency

Reliable distribution of life-sustaining water to urban residents is a requirement of civil life. To satisfy this need, extensive distribution networks are used to bring water within reach of all citizens (see Exhibit 61). These networks must withstand an array of challenges such as pressure transients, corrosion processes and contamination sources.

Within South Asia, the performance of urban water utilities varies from city to city, but they typically offer poor service delivery, poor maintenance of physical systems, and poor recovery of costs (HPEC 2011). Many South Asian water utilities face difficulties in accessing and distributing sufficient water supply to meet growing demands, and markets for alternative water sources based on private assets (boreholes, trucks, etc.) are growing in many cities.

Municipal utilities in South Asia suffer from high levels of non-revenue water (NRW). NRW is water that has been sourced and prepared for distribution, but is lost before it reaches the customer. NRW losses of 50% are not uncommon in South Asian cities. Losses can be physical losses (through leaks, also referred to as technical losses) or apparent losses (for example through theft or metering inaccuracies).

From a human development perspective, physical losses are the most critical because they represent potentially available water that is not ultimately used for people's welfare. Apparent losses are also important, particularly regarding the economic sustainability of a water utility, but they pose less humanitarian concern because they represent water that is actually used by people.

In a broader context, physical losses from a water utility perspective are not ultimately lost in a river basin perspective, and leaked water may be accessed later as groundwater or may sustain urban vegetation.

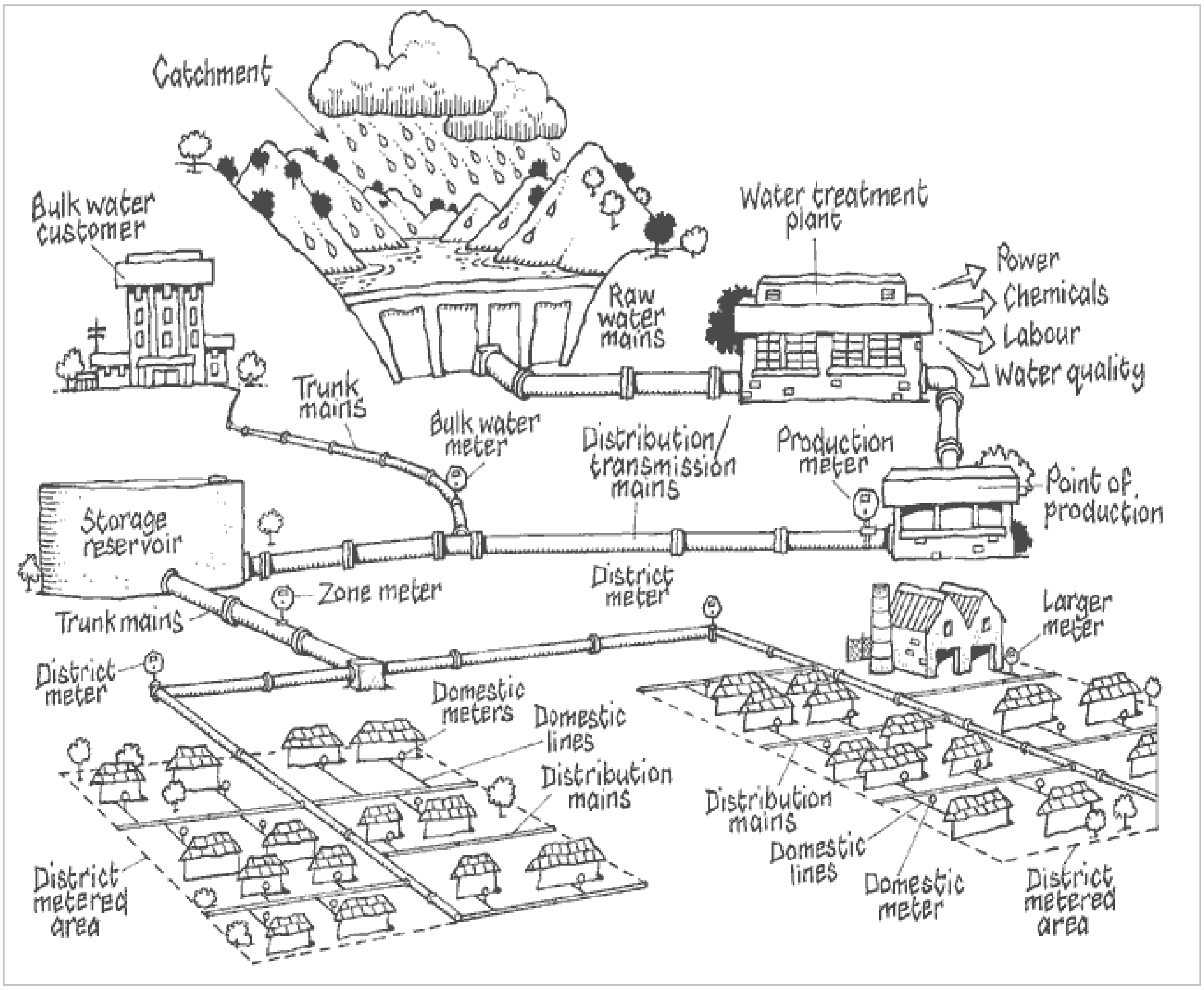

Exhibit 61. Urban water supply systems typically consist of surface water catchment and/or groundwater extraction, followed by treatment, storage and distribution to consumers. Metering of water flows at multiple points is important for effective management and billing, but is not commonly done in South Asian practice. (Source: Open University 2016)

The most commonly used indicator to measure water losses is the percentage of NRW as a share of total water produced (see Exhibit 62). Other useful indicators include losses per kilometre of network and losses per connection. In general, urban water distribution losses are poorly understood and documented in quantitative terms.

In a survey of Indian cities, the Government of India's Ministry of Urban Development found NRW values averaging 44%, and ranging from less than 20% to greater than 60% (India Ministry of Urban Development 2010) (see Exhibit 63). About three-quarters of NRW is real physical losses of water through leakage, and one-quarter of NRW is apparent loss due to theft or meter errors (HPEC 2011; Raj 2013).

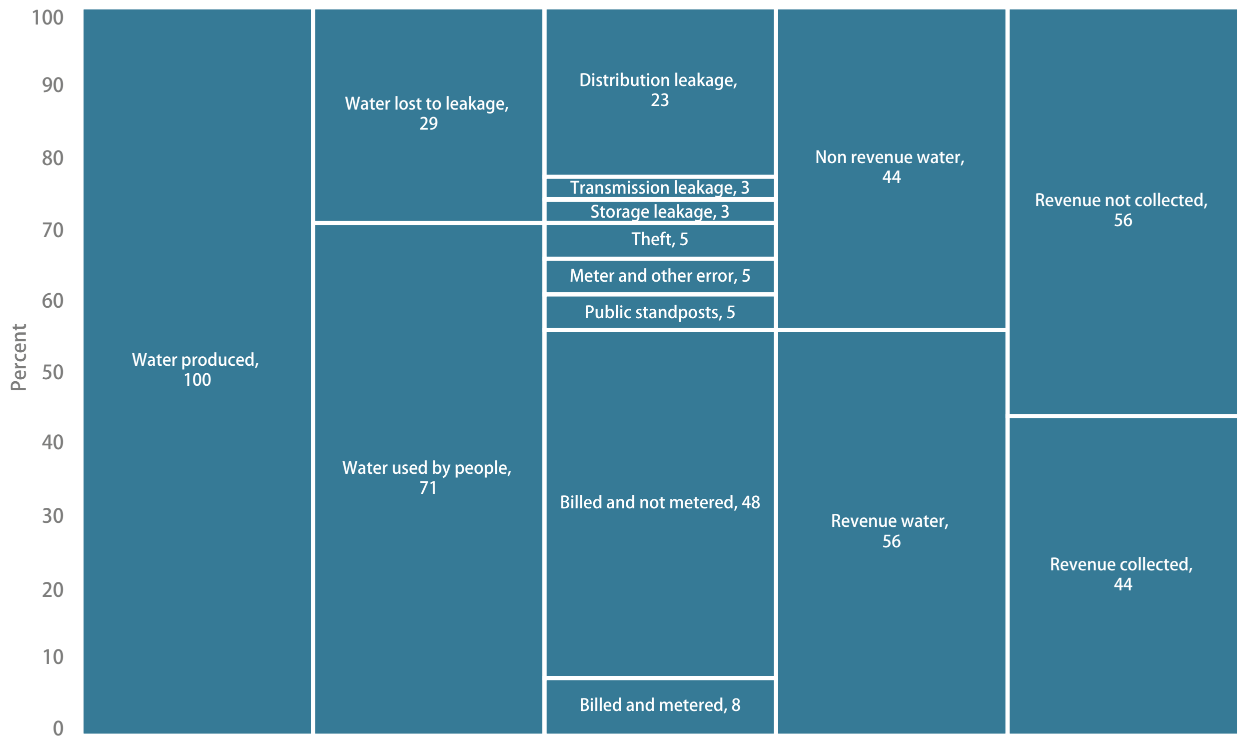

Exhibit 62. Water balance of a typical South Asian urban water utility, in percent. (Source: ITT analysis based on India Ministry of Urban Development 2010, HPEC 2011, Raj 2013)

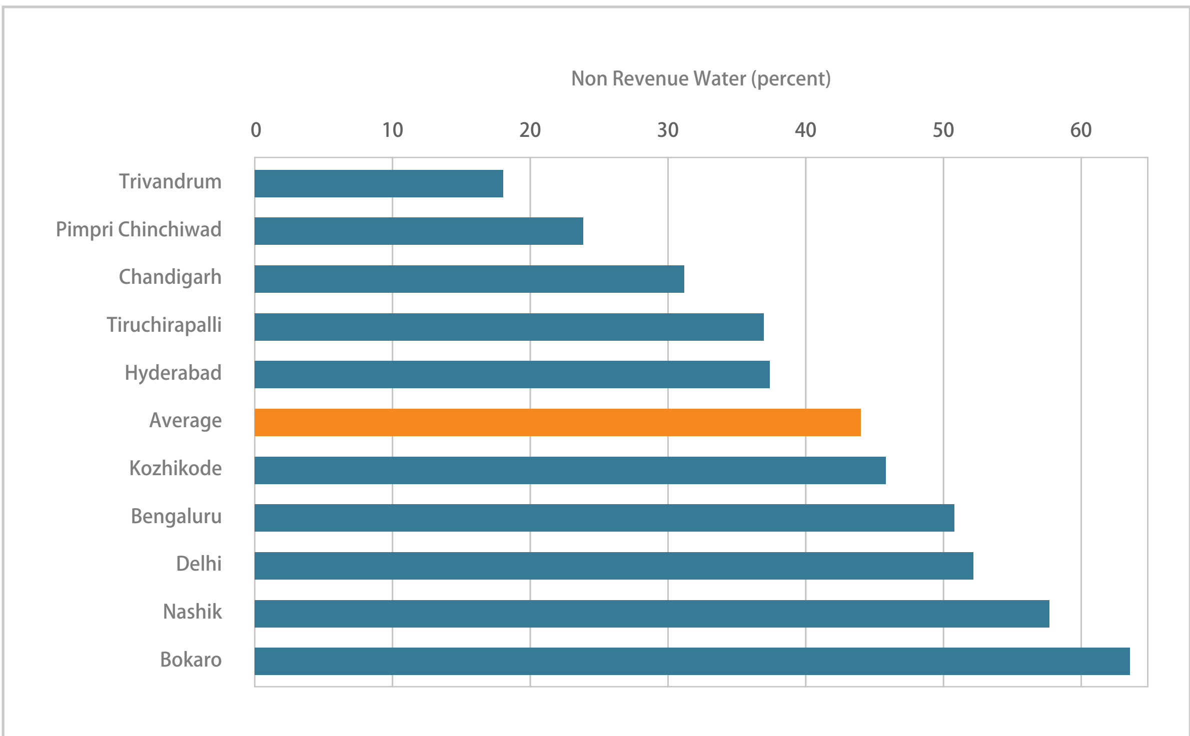

Exhibit 63. Extent of non-revenue water varies strongly from city to city. The average NRW among Indian urban water utilities surveyed was 44%. (Source: data from India Ministry of Urban Development 2010; survey conducted 2008-09; only cities with a data reliability grade of "A" or "B" are shown)

Intermittent water supply (IWS) is an important factor in the poor performance of South Asian water utilities. Water is not available continuously to all households and industries, but instead is provided in turn to different urban zones, each for a limited period (see Exhibit 64). There are many drivers of IWS, including physical water supply constraints due to seasonal and population trends, limiting water leakage from damaged pipes, and prioritising access due to privatisation or local governance policy. Galaitsi et al. (2016) described three types of IWS, listed from least disruptive in consumers' lives to most disruptive:

- Predictable Intermittency, with water supply that generally occurs on a predictable and anticipated schedule
- Irregular Intermittency, with supply arriving at unknown intervals within short time periods of no more than a few days
- Unreliable Intermittency, with uncertain delivery time and the risk of insufficient water quantity.

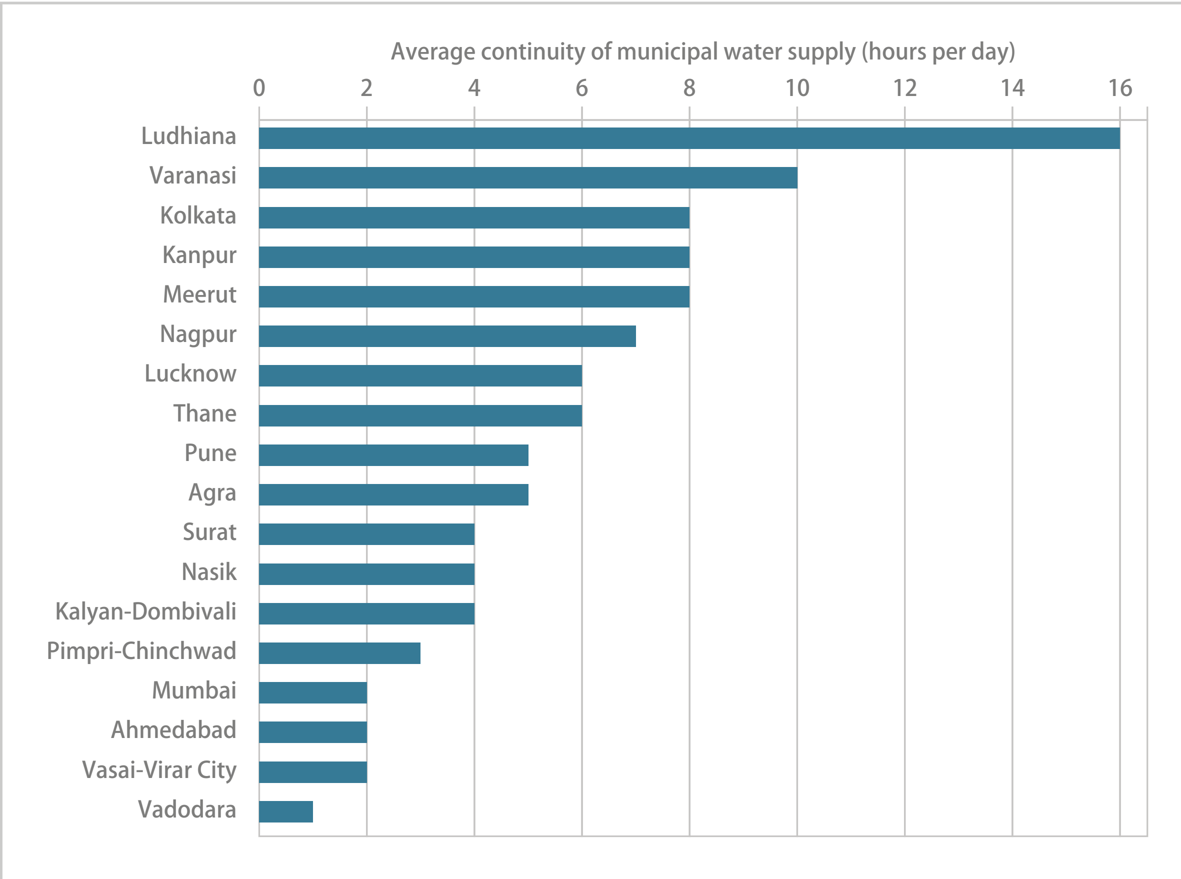

Exhibit 64. Municipal water supply in South Asian cities is typically intermittent and is not continuously available to consumers. (Source: data from CEPT 2014)

Households develop coping strategies for IWS, such as storing water when it is available for use later. Nevertheless, IWS is emerging as an important obstacle to urban water security (Kumpel & Nelson 2014, 2016; Galaitsi et al. 2016), for several reasons:

- Intermittent lack of pressure within the pipes allows contaminated water from outside the system to enter through holes or cracks in the pipes
- Pressure fluctuations tend to damage the pipes and connections, leading to water leakage and contamination
- Intermittent stagnation allows growth of biofilms within pipes, leading to microbial contamination
- Water held in household tanks can become contaminated by improper storage and access methods
- During times when intermittent water is flowing, profligate usage leads to high levels of waste
- Water meters malfunction due to pressure surges and air bubbles created by intermittent pressurisation
- Social conflicts arise due to unequal access to water by different zones of urban areas
- Prolonged shut-offs of municipal water require some households to rely on costly private water options.

Globally, substantial experience has been accumulated in successfully distributing continuous water supply throughout large cities. Best-practice recommendations have been developed for broad actions to reduce NRW and IWS, including complete metering of production and consumption, improved billing and collection, identification and repair of visible and invisible leaks, and elimination of illegal connections (ADB 2005, 2010).

Numerous methods and tools have been developed for managing losses in water distribution systems (Mutikanga et al. 2013). Illegal connections can be physically identified and removed, though political and economic factors play large roles in their definitive solutions. Effectively managing physical losses (leakage) in distribution systems requires active control measures, speed and quality of repairs, and effective pressure management.

Metering of water flows (described in detail in Section 6.3) at multiple points throughout a municipal water utility system is important to identifying leakage and managing municipal water flows. There are considerable economic considerations in investing in leakage reduction measures in urban water supply systems (Kumar 2014).

Modern flow metering, pressure management and data capture technologies can quickly identify burst pipes, and estimate the gradual accumulation of smaller leaks (Simbeye 2010). Dividing the network into sub-zones such as district metering areas (DMA) can effectively quantify losses within the region. Similarly, bulk meter zones at production sites or water inlets can help in isolating transmission leaks.

Flow meters can only detect the general area of leakage but cannot pinpoint the exact location of a leak. For this, sensors such as ultrasonic noise loggers, leak noise correlators and ground microphones are manually applied to the pipelines to detect the exact location of the leakage for repair.

Another important tool to reduce urban water loss is pressure management, as leakage rates are very sensitive to system pressure. The rate of leakage in water distribution networks is a function of the pressure applied by pumps or gravity. There is a direct physical relationship between the water pressure, and both slow leakage rate and the frequency of burst pipes.

The most common and cost-effective measure is automatic pressure reducing valves (PRV). PRVs are installed at strategic points in the network to reduce or maintain network pressure at a set level. The valve maintains the pre-set downstream pressure regardless of upstream pressure or flow-rate fluctuations (Prescott and Ulanicki 2008). Other pressure management measures include air relief valves to release negative pressures or air bubbles in a pipeline, variable speed controllers, and break pressure tanks.

An important technological advance in improving urban water management is supervisory control and data acquisition systems (SCADA). SCADA enables acquiring data from remote devices such as valves, pumps and sensors, and allows overall system control from the utility office. This provides precise process control to efficiently provide water throughout the network. SCADA host platforms provide functions for graphical displays, alarms, trend analysis and historical operations data. Integrating data from household water meters, district metering areas, and utility transmission meters, SCADA can allow central monitoring and detection of water losses (see Exhibit 65).

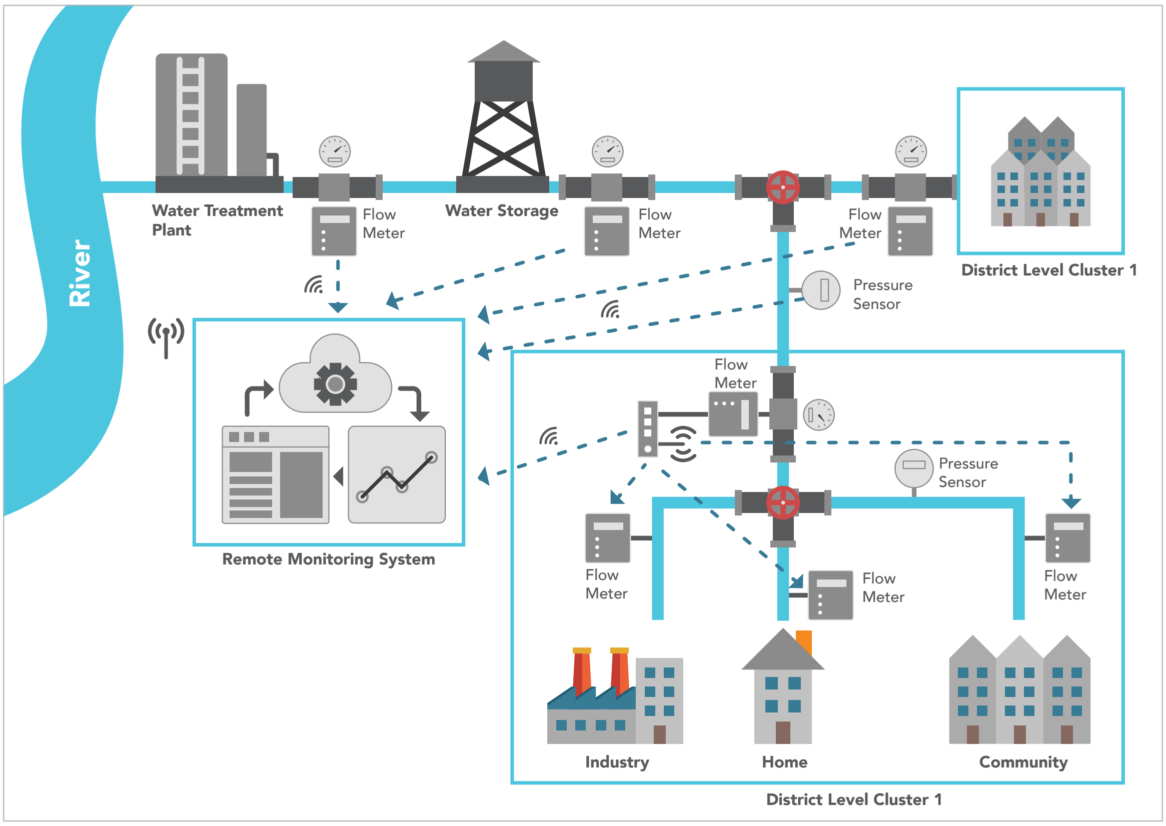

Exhibit 65. An example of a smart water distribution system. (Source: adapted from Farley et al. 2008)

Notwithstanding the accumulated global best practices for urban water distribution, South Asian municipal utilities are currently challenged to provide their inhabitants with continuous supply of high-quality water. Private markets for household water are expanding in many cities to satisfy unmet demand.

IWS, in particular, is impeding the adoption of improved water utility management practices such as metering and automated control systems. These best-practice approaches require continuous water supply and cannot be applied where pressure is supply-driven rather than demand-driven (Kumpel & Nelson 2016). In systems that are intermittently pressurized, as is common in South Asia, the analytical water balance approach cannot be used, and automated control systems are currently unable to operate with non-continuous water supply. IWS can cause malfunctioning of monitoring equipment and incorrect water flow measurements due to air pockets, vacuums, and repeated drying and wetting. IWS also causes premature wear of the infrastructure, further contributing to losses and intermittency.

Though challenging, increasing the distribution efficiency of urban water is a significant lever for improving water security in South Asia. If Indian cities were to reduce their NRW loss from the current average of 44% down to a target average of 15%, about 4.4 km^3 of physical water leakage would be avoided per year.[11]

6.2.2 Irrigation water conveyance efficiency

South Asia has a large canal system to distribute irrigation water. River water is diverted by barrages and weirs into main canals, then branch canals, distributaries and minors, before arriving at farmers' fields. Most canals are unlined earth canals and leak significant water into the ground. Depending on rainfall and soil characteristics, canal leakage (as well as farm field infiltration) can comprise a significant source of groundwater recharge (see Exhibit 66). Thus the leaked water is not truly lost, in a river basin perspective, because it can be abstracted as groundwater and used.

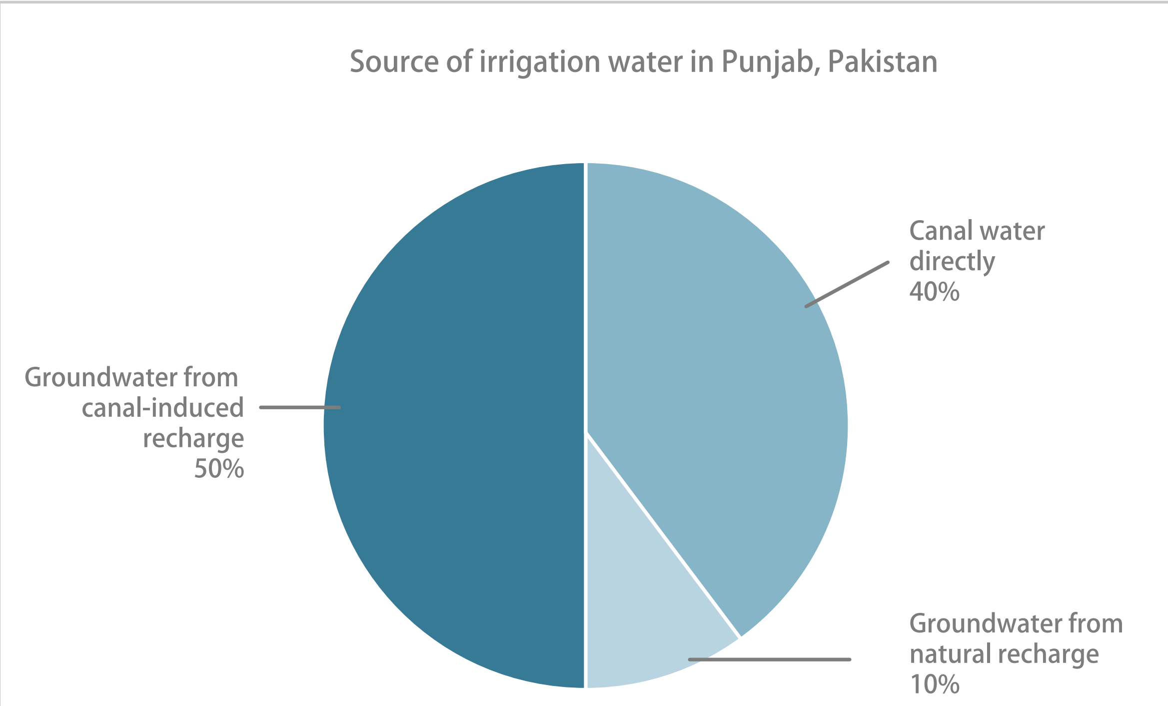

Exhibit 66. Half of irrigation water in Pakistan's Punjab province is from groundwater recharged through canal leakage and infiltration of canal-delivered water. (Source: data from World Bank 2005b)

[11]Assuming 75% of NRW is from physical losses from leakage, and 25% apparent losses from theft.

Canals may be lined to reduce leakage. Concrete is conventionally used for canal lining, though other materials including modern polymers are available. Lining canals can partially (though not fully) reduce leakage, but is seldom a permanent solution because cracks and perforations develop and leakage increases over time. Canal lining is unlikely to significantly enhance water security, particularly in areas of fresh groundwater where canals transport run-of-river water diverted by barrages. There are, however, at least three instances where canal lining can contribute to local water security:

1. In areas of saline groundwater, from where the leaked water cannot be recovered by borewells,
2. When the transported water has been stored inter-seasonally in a reservoir, thus the water is more valuable than diverted run-of-river water,
3. In areas at risk of waterlogging, where groundwater recharge is excessive.

6.3 Water metering for management and billing

Metering of water does not directly affect the amount of water used. However, combined with a suitable water pricing structure, metering may act as an economic incentive to adopt water-saving behaviours and technologies. Metering and pricing of water may be an essential prerequisite to adopt other water-saving technologies (Garrick et al. 2017). Water volume may be measured and billed directly, for example water used by urban households. Alternatively, water use may be metered and billed indirectly, based on electricity used for groundwater pumping for irrigation.

In addition to metering to enable accurate water billing, metering of water flows at multiple points throughout a municipal water utility system is a necessary component of finding and eliminating leaks and theft, to reduce non-revenue water. In general, metering is an essential step to understanding and effectively managing municipal water flows: "you can't manage what you don't measure."

A variety of water meters are available, based on different principles of operation (Boyle et al. 2013). Most residential and small commercial applications use mechanical positive displacement meters, which use oscillating pistons or disks to measure the volume of water that passes through. Other commonly used water meters measure the velocity of water through a fixed area, from which water volume can be determined.

Water velocity is commonly measured with mechanical meters such as jet meters and turbine meters. Non-mechanical methods such as electromagnetic and ultrasonic meters can also be used to measure water velocity. Electromagnetic meters apply a magnetic field to the metering tube, and determine the flow velocity in the tube based on electromagnetic induction. Ultrasonic water meters use transducers to send ultrasonic sound waves through the water to determine its velocity, based on either the Doppler effect or the transit time between two fixed points.

After a meter is used to measure the amount of water consumption, that information must be conveyed to the water utility to enable billing and collection. Traditionally, water meters were read manually by workers walking house to house. More recently, various electronic means have been developed to automatically convey meter readings to the water utility. Automated meter reading (AMR) can increase accuracy and timeliness of metering (Hauber-Davidson & Idris 2006). An automated meter can calculate the flow rate at a client connection, and communicate the data remotely to the host platform along with its GPS/GSM details. AMR technologies are currently expensive but have the potential to be mass manufactured allowing high deployment of efficient smart meters for all end-users, to aid in accurate billing and management.

Several technology levers aim to increase water supply, to provide more water to be used:

6.4 Capture and store rainwater

The rationale for capturing and storing rainwater in South Asia is to overcome the strong seasonality of precipitation. During much of South Asia, the majority of annual rainfall occurs during just a few months of the monsoon season. Little rain falls during the remainder of the year. All water supplies, including groundwater and surface water, ultimately originate from precipitation. For example, some monsoon rainwater infiltrates into the soil, from where it provides baseflow for perennial rivers, and from where it may be extracted as groundwater from wells during dry seasons.

Beyond this natural water cycling, however, it may be advantageous to use engineered infrastructure to directly capture rainwater during the monsoon and store it for later use. This may take several forms, including small-scale surface storage (e.g. household-level rooftop capture and storage in tanks, and farm-level capture of run-off and storage in ponds), large-scale surface storage (e.g. impoundment of river water in reservoirs behind dams), and managed aquifer recharge (using surface structures to divert water run-off towards underground aquifers). A related approach, atmospheric water capture, seeks to extract water vapour from the air even before it falls as rain.

There is large geographic variation across South Asia in terms of the average annual rainfall, which determines the amount of rainwater resources available for capture in any given region (see Exhibit 67). In general, the wetter regions of South Asia include Bangladesh, eastern India, and western coastal India. The dryer regions include Pakistan and north-western India. A further challenge is introduced by year-to-year variability in rainfall: drier areas not only receive less rainfall on average, but also have more variable rainfall from year to year around that average (see Exhibit 68).

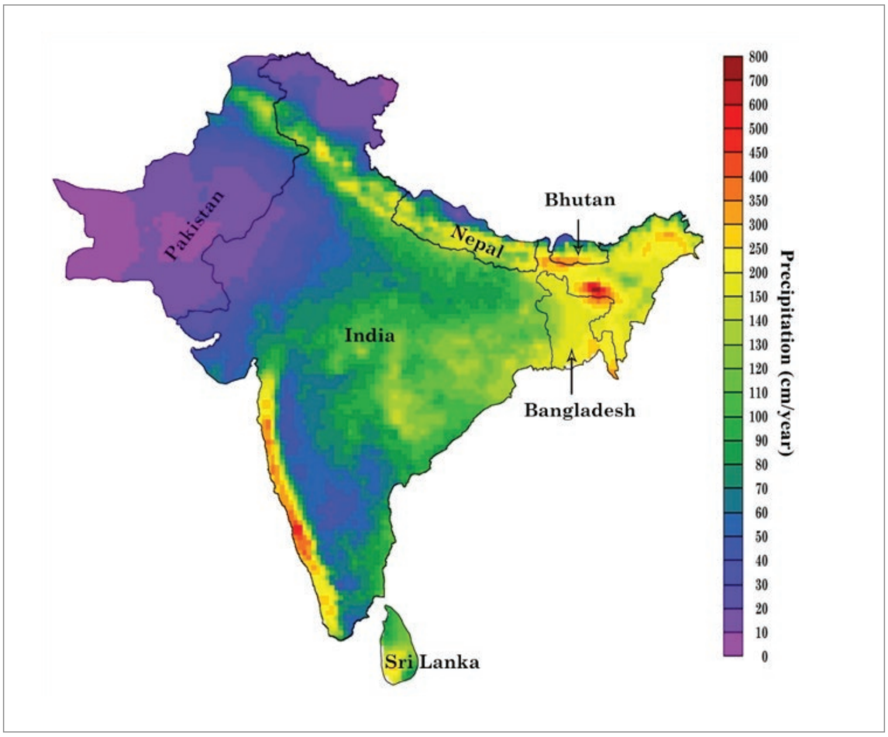

Exhibit 67. Average annual precipitation in South Asia varies widely by location. In general, western regions are dryer, and eastern regions are wetter. (Source: Mukherjee et al. 2015)

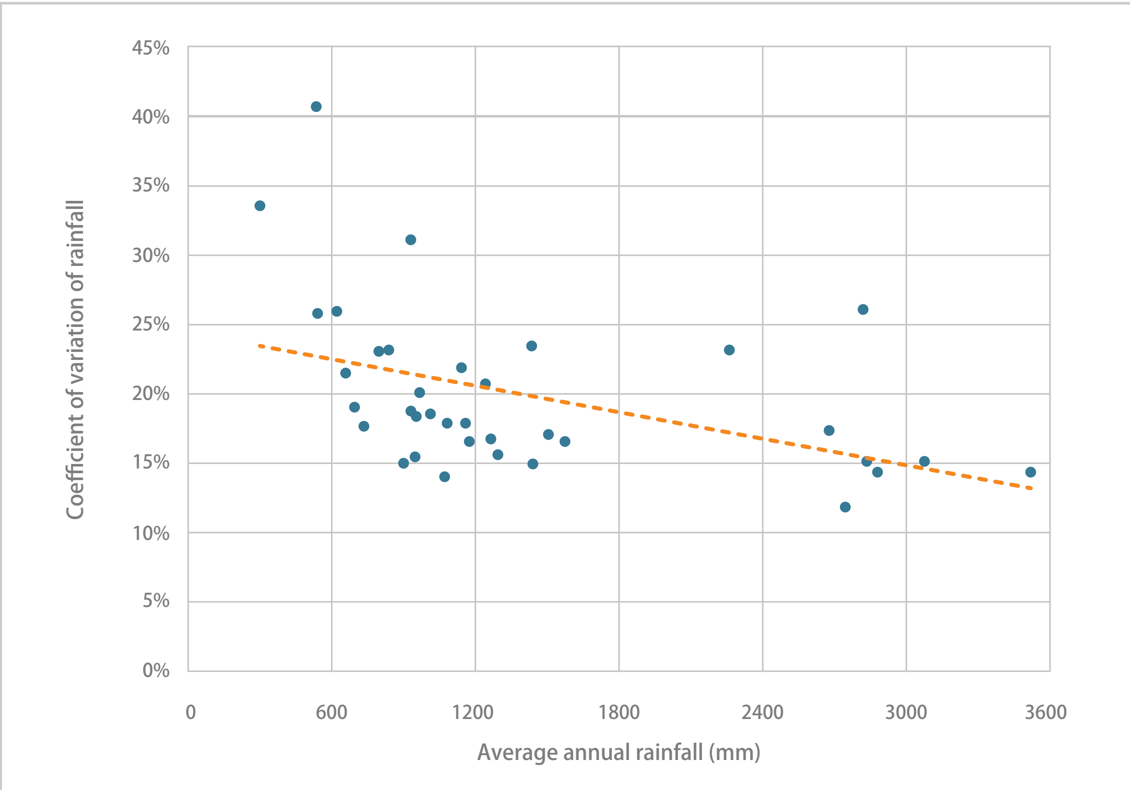

Exhibit 68. Drier regions tend to have not only less average precipitation, but greater year-to-year variation in precipitation. The graph's horizontal axis shows average annual precipitation in each of the 36 meteorological subdivisions of India from 1951 to 2014, and the vertical axis shows year-to-year variability of precipitation in each of the 36 regions (expressed in percent terms, as the standard deviation divided by the average from 1951 to 2014). (Source: ITT analysis based on Kumar 2004, with updated data from Government of India 2017)

These three sources of rainwater variability (geographic, seasonal and year-to-year) pose significant challenges to the sufficiency of water supply based on rainwater capture and storage. Water is fundamental to life, so reliable daily access is a must. Household water supplies that become exhausted during the dry season, or during a dryer-than-average year, are inadequate. Households may have a primary water source and several supplementary sources, but at least one source must be functional each day, for healthy and hygienic domestic life.

While rainwater capture and storage will bring benefit to the user, it may negatively affect potential downstream users (Kumar et al. 2008). Within closed river basins, capturing more rainfall upstream necessarily means that downstream users receive less water. While likely inconsequential at small scale, the creation of large dams and reservoirs or the eventual wide-spread implementation of rooftop rainwater capture would significantly alter regional hydrology and should be planned for accordingly.

6.4.1 Small-scale rainwater harvesting and storage

Rooftop collection followed by household-level tank storage is an option for rainwater capture and storage. It is instructive to compare the amounts of rainwater falling on house rooftops in different South Asian cities, to the amount of water used by the households. Potential rainfall capture volume is determined by the local precipitation and by the size and quality of the rooftop. In most parts of South Asia rooftop capture will likely be, at best, a supplemental source of household water (see Exhibit 69). Our analysis shows that household drinking water requirements could be satisfied by rooftop capture in most cities and house sizes, but total household water requirements could only be satisfied by large houses in rainy cities.

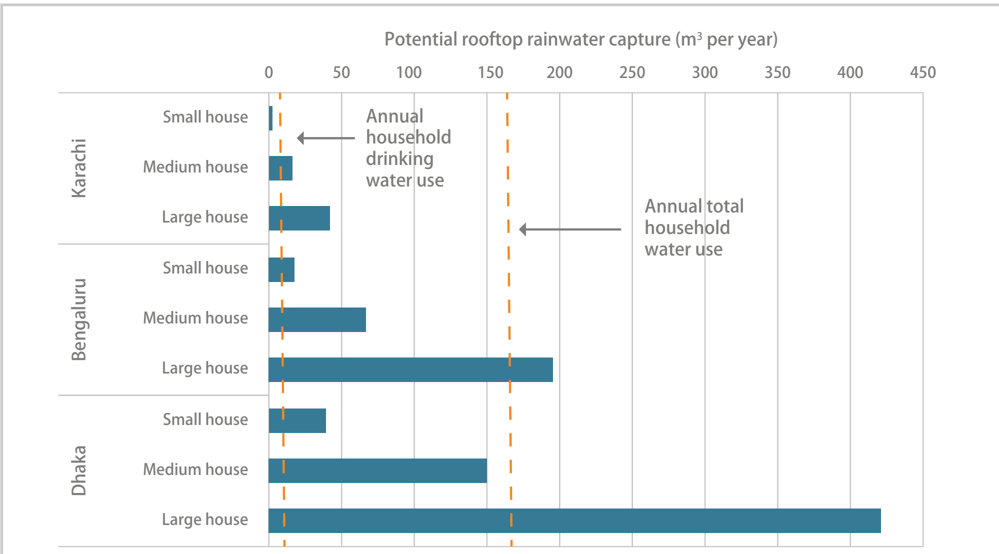

Exhibit 69. The amount of rainfall that may be captured by a household depends on the local annual precipitation, and on the size of the rooftop capture area. Here we show the potential for rainwater capture in three locations (dry: Karachi, moderate: Bengaluru, wet: Dhaka) for three different house rooftop sizes (small: 20 m^2, medium: 70 m^2, large: 200 m^2). Also shown is the estimated annual drinking water requirements (7 m^3 per year), and total household water requirements (167 m^3 per year), for a household of five people. Drinking water requirements could be satisfied by rooftop capture in most cities and house sizes, but total household water requirements could only be satisfied by larger houses in wetter cities. (Source: ITT analysis based on average annual precipitation data from Wikipedia 2017 and average per capita water consumption data from Shaban & Sharma 2007)

Assuming adequate precipitation and capture surface are available, a further challenge is storing sufficient quantities of water for use during later dry periods. Storing a 6-month supply of drinking water for a household of five people would require a reservoir of 3.6 m^3 capacity, while storing a 6-month supply of total household water would need 82 m^3.

Based on current prices of common plastic storage tanks, and assuming a generous 20-year tank lifespan, the lifecycle cost of each m^3 of drinking water obtained from the storage would be almost 7 USD, and each m^3 of household water would cost over USD 12. Rooftop rainwater capture and storage for domestic use will therefore likely continue to play a minor role in South Asian water supply, due to limited capture area and expensive storage volume. In regions of high and regular rainfall, however, it may be locally important (Bashar et al. 2018).

Another form of small-scale rainwater harvest and storage with greater potential is farm-level capture of run-off followed by storage in small constructed reservoirs or ponds, often called "tanks". This is more feasible because the surface area for run-off capture can be much larger, and the cost per unit volume of storage is much less than that of tanks made of plastic, metal or masonry. However, the quality of water collected in such ponds is lower, thus the stored water will likely be suitable for agricultural uses but not directly for household uses. Water storage in small constructed reservoirs or ponds is still very important in south Asia, particularly in southern India, irrigating about 4 million hectares of farmland in India.

In most South Asian cities, the total amount of rain that falls annually within the city boundaries is substantially greater than the total amount of domestic water used by the city's inhabitants (see Exhibit 70). However, although the gross urban rainwater supply is abundant, inadequate rooftop collection area and costly tank storage pose significant challenges. Other potential options to economically capture and store a significant fraction of the gross rainfall include large-scale storage in reservoirs and aquifers (see next sections).

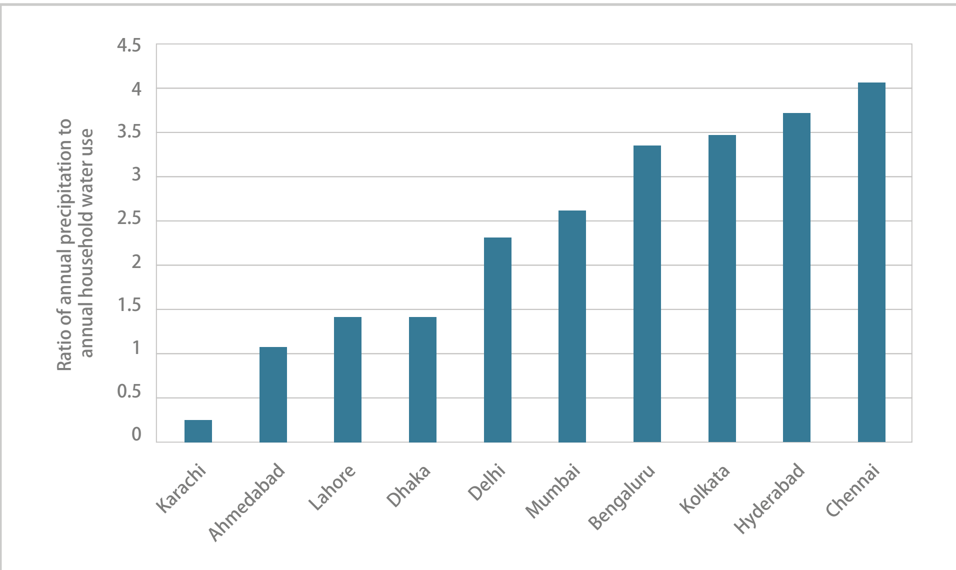

Exhibit 70. The total annual rainfall that falls within city boundaries is typically greater than the amount of water consumed by the city's households. Graph shows the ratio of total annual precipitation to total annual household water use, for selected South Asian cities. (Source: ITT analysis based on average per capita water consumption data from Shaban & Sharma 2007, average annual precipitation data from Wikipedia 2017, and city population and land area estimates from Demographia 2016)

6.4.2 Large scale surface water storage

Where conditions are suitable, large quantities of river run-off can be captured behind large dams and stored in reservoirs, from where it may later be released and used on demand. Surface water in South Asia is predominately used in run-of-river systems, which employ barrages to divert flowing river water into canals for distribution to farms and cities.

Less prevalent in South Asia are storage systems, which accumulate water behind dams thus moderating seasonal and annual variation in precipitation. Although some individual dams in South Asia are among the world's largest (e.g. Tarbela and Mangla in Pakistan and Tehri and Bhakra in India), the per capita water storage capacity in South Asia is low compared to other global regions (see Exhibit 71).

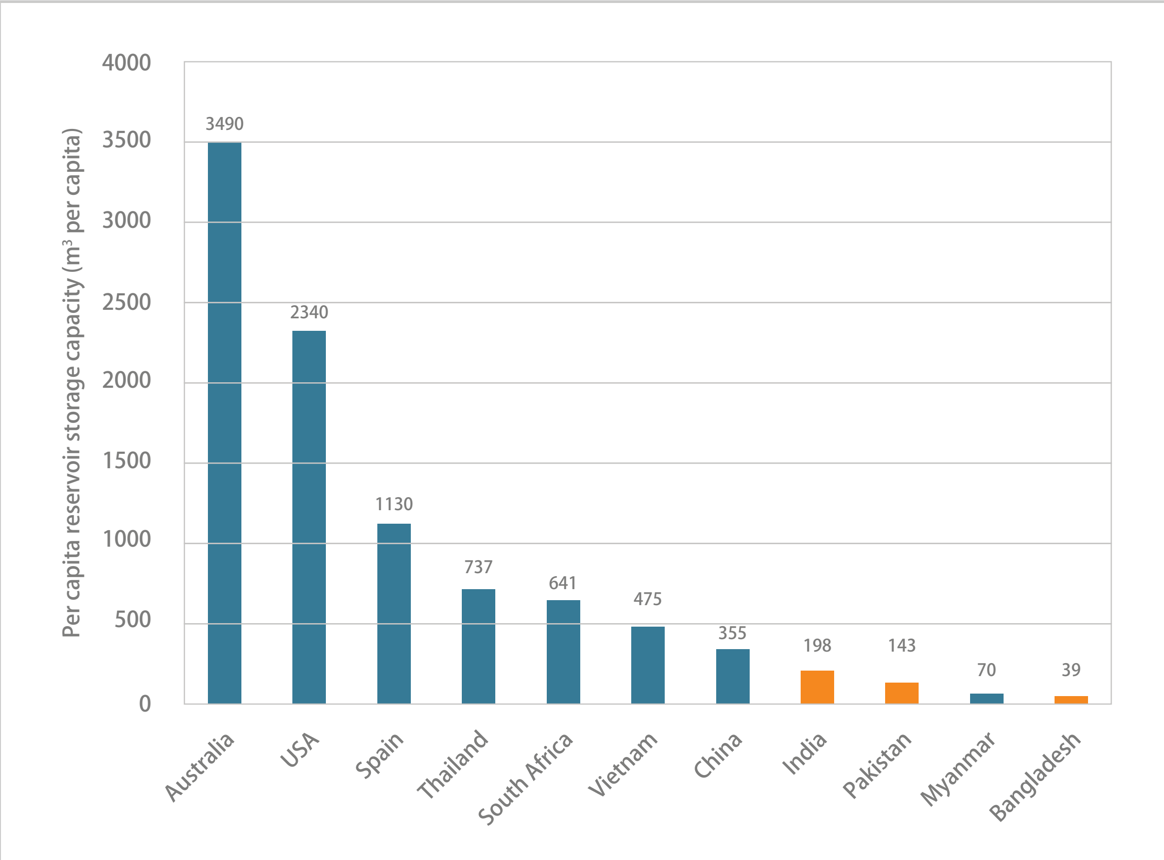

Exhibit 71. Per capita reservoir live storage capacity for selected countries. (Source: ITT analysis based on reservoir capacity data (circa 2016) from FAO 2017c; population data (2017) from UN 2017)

Within South Asia, there is much variation between river basins, in terms of reservoir storage. Some river basins have installed storage capacities exceeding 50% of total annual river flow (e.g. Krishna, Godavari and Tapi Rivers), while others have much lower proportional storage capacity (see Exhibit 72). Potential for dam construction and reservoir creation is first determined by numerous physical factors such as landscape topology and geology, which are limiting in many South Asian regions. Decisions to build dams are also affected by economic and social considerations.

Within each river basin, diminishing returns are found from creation of additional storage capacity, as basins approach closure (see Section 3.1). Within closed basins, new dams will not increase total surface water supply, but merely redistribute the supply. Dams can be an effective tool for river flood control (discussed in Section 6.10.2).

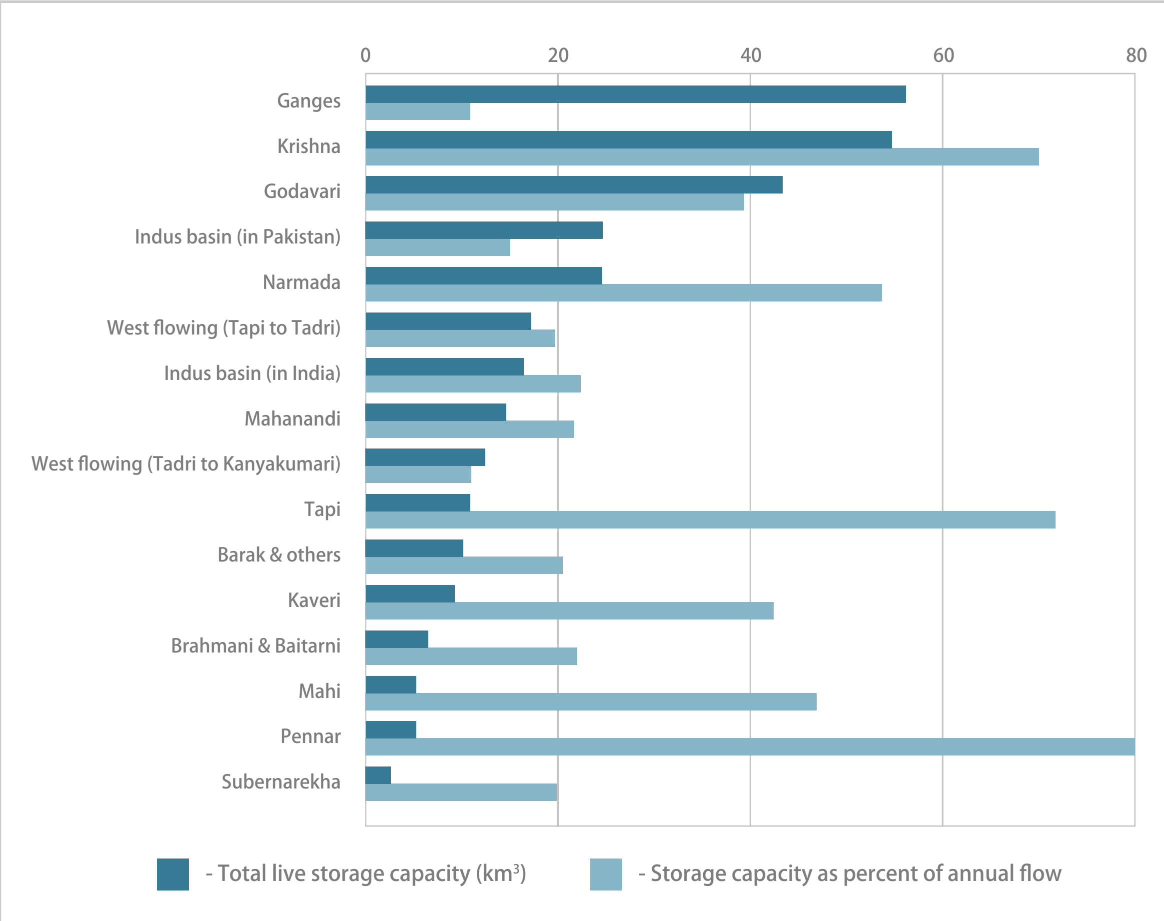

Exhibit 72. Live water storage capacity varies considerably among South Asia's river basins; the Ganges, Krishna and Godavari basins have the greatest storage capacity. In river basins where storage capacity is a large proportion of annual river flow (such as the Krishna, Tapi and Pennar basins), creation of additional storage capacity will result in little additional water supply. (Source: India data from CWC 2015; Pakistan flow data from Pakistan Bureau of Statistics (2014); Pakistan storage data from Exhibit 73; live storage capacity includes completed and under-construction projects)

Natural siltation from Himalayan rivers is very high. In particular, the Indus is one of the largest sediment producing rivers in the world (WCD 2000). The main source of sediment is glacial melt and erosion from steep barren slopes. Filling of reservoir storage capacity by sediment is a serious ongoing problem in Pakistan, and new dams must be built simply to maintain existing storage capacity, to avoid a progressive reduction in active storage volume (see Exhibit 73). Sediment flow in the Indus River averages 136 million tonnes per year, for which dredging is impractical (Archer et al. 2010). By altering the transport of fluvial sediments, dam construction also plays an important role in the geomorphology of rivers, the fertility of floodplains, and the nutrient balance of rivers and estuaries (Dandekar 2014).

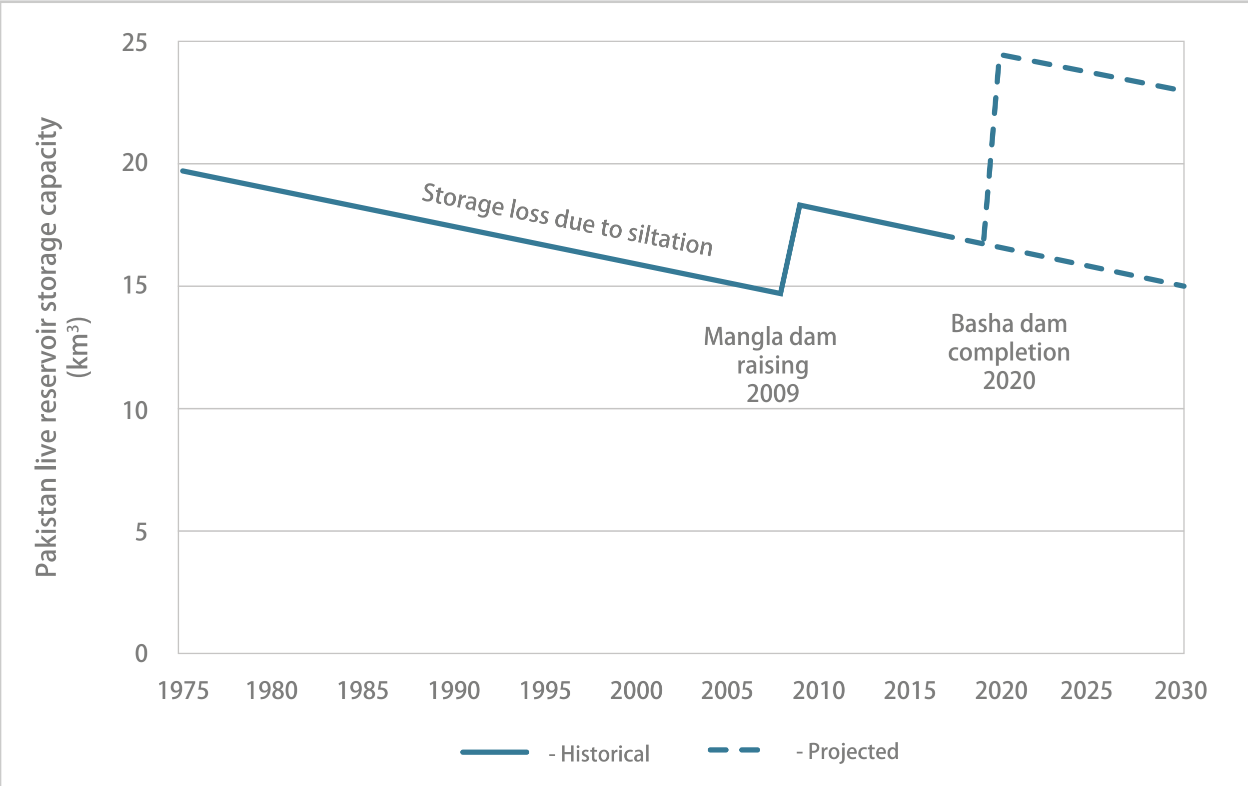

Exhibit 73. Live water storage capacity behind Pakistan's dams decreases continually due to sedimentation, and is increased periodically by building new dams or raising existing dams. (Source: World Bank 2005b, updated by ITT)

While dam construction should not be dismissed as a technology for improving water security in South Asia, neither should it be seen as a definitive solution. In river basins with current low storage capacity, adding well-designed dams will augment total usable water supply. In basins approaching or already at closure, which are typically the most water stressed, additional dams will not contribute to improving water security.

6.4.3 Managed aquifer recharging

Underground aquifers store vast amounts of water, which can be accessed by pumping from wells. The capacity for groundwater storage in South Asia is much greater than surface reservoir storage capacity. Some deep aquifers contain "fossil water" that was stored long ago and does not circulate, unless accessed and extracted by wells. Most aquifers, however, are dynamic and receive newer water via recharge mechanisms, while losing older water via natural discharge to rivers and oceans, and via groundwater pumping.

Many regions of South Asia are currently extracting groundwater faster than the rate of natural recharge, leading to falling water tables (see Sections 3.2 and 3.3). The rate of natural aquifer recharge is also diminishing, due to rapid urbanisation and land use changes that have reduced the infiltration of water into the soil. Managed aquifer recharge (MAR) seeks to increase the rate of groundwater recharge, to allow greater rates of groundwater extraction without risk of water table decline.

MAR is achieved by reducing the fraction of rainwater that runs off the land surface, thus increasing the fraction that infiltrates through the land surface and enters the soil. This is typically implemented through engineered structures that slow the downstream flow of surface run-off water, allowing more of it to infiltrate into the ground (CGWB 2007). A wide range of structures are available at varying scales, including farm-level swales, check dams, percolation tanks and ponds, dams and barrages (see Exhibit 74).

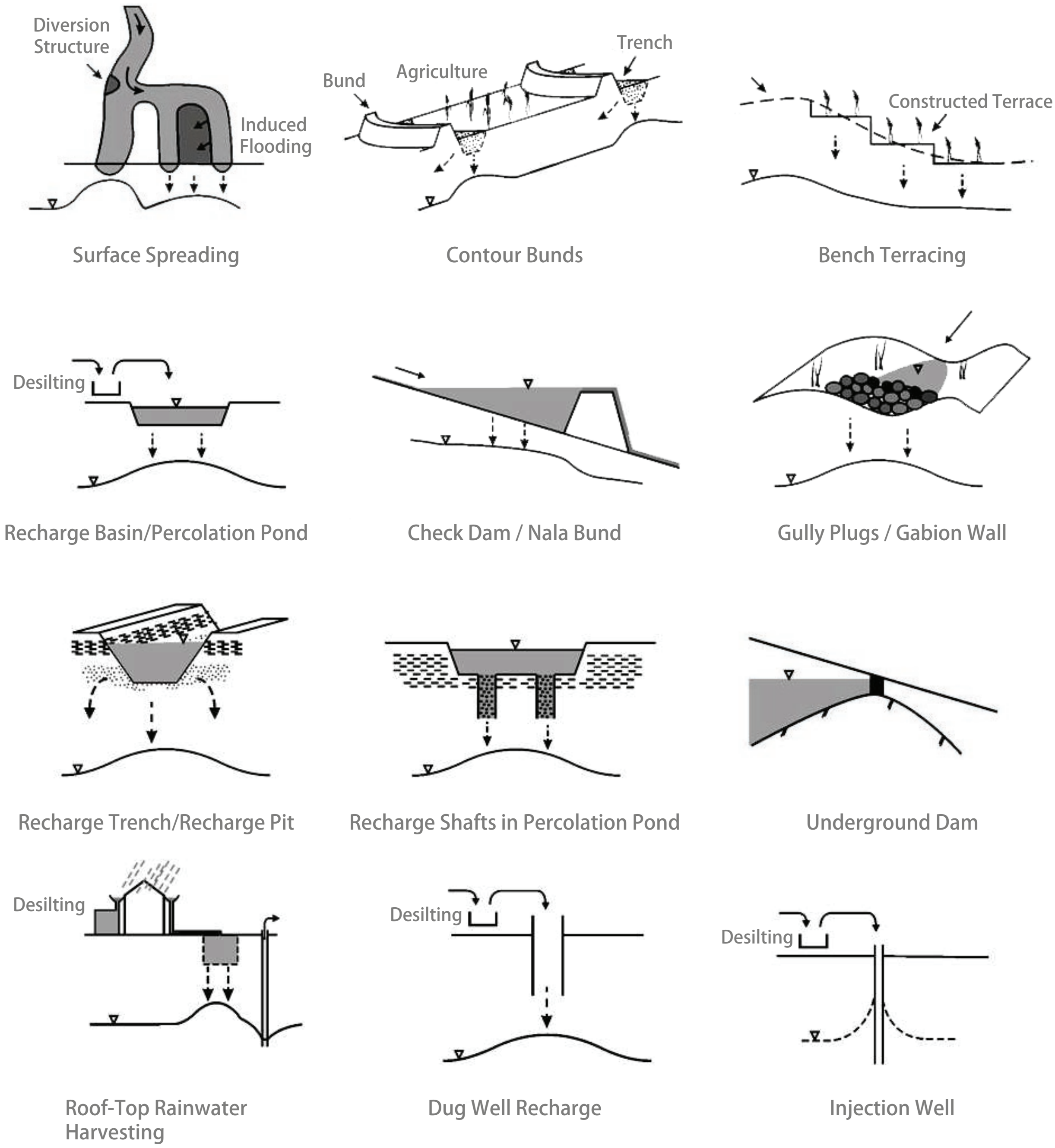

Exhibit 74. Types of managed aquifer recharge structures, and their effects on local water table. (Source: adapted from SaphPani 2012)

MAR is suitable only in locations of adequate rainfall (to create a surplus of water to be stored) and suitable geology (porous underground formations to transfer and store the water). In a national master plan for artificial recharge, CGWB (2013) estimated that about 29% of total land area of India is suitable for MAR. They estimated that about 86 km^3 of run-off water may be managed annually to recharge groundwater in India, in addition to existing natural aquifer recharge. This quantity corresponds to about 38% of the current total annual groundwater extraction in India.

There are significant uncertainties regarding these estimates, and the actual potential of MAR in South Asia remains under debate (BGS 2006). More certain, however, is that the potential benefits of MAR vary widely by location. This is because MAR requires three conditions: the availability of uncommitted surface water, the availability of underground storage space, and the demand for groundwater (Shah 2008).

MAR has numerous limits as a means to increase groundwater resources. In dryer regions, the amount and timing of rainfall limit the amount of run-off that may be harnessed to recharge groundwater. In regions with unsuitable geology, even if seasonal water is plentiful, there may be inadequate aquifer porosity to store significant water, or there may be natural barriers between the surface run-off and underground aquifer.

In closed river basins, MAR will not increase total water supply even if local run-off and geology are suitable, because an upstream user's gain will lead to a downstream user's loss. Furthermore, the effects of future climate change on aquifer recharging is uncertain. The amount, timing and intensity of precipitation are projected to change, though its effect on the partition of rainwater into run-off and infiltration will vary by location (see Exhibit 75).

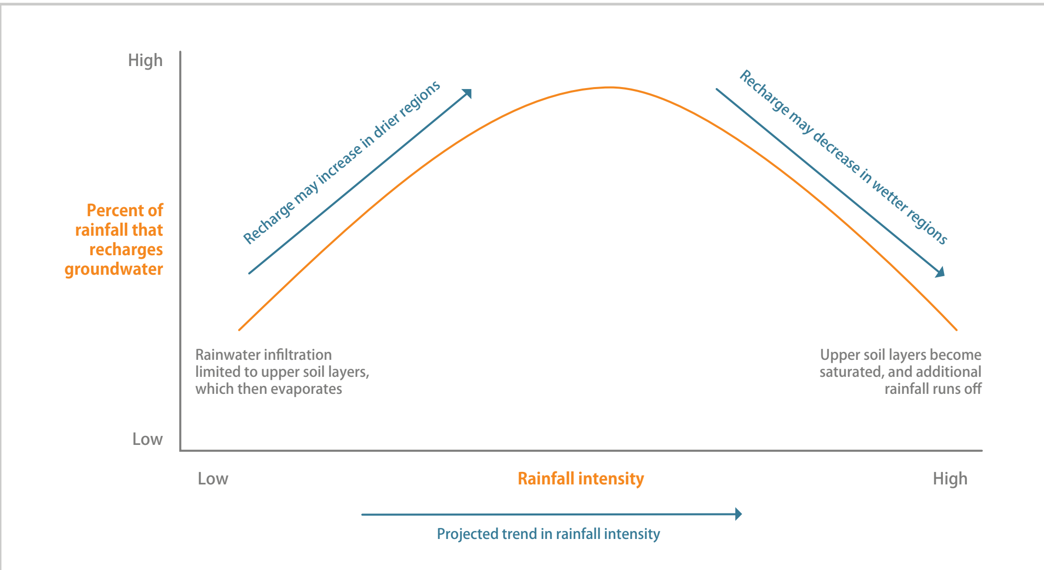

Exhibit 75. Rainfall intensity in South Asia is projected to increase due to global climate change, which may have variable effects on groundwater recharge. (Source: ITT analysis)

Nevertheless, where conditions are suitable, MAR may significantly contribute to regional water security by increasing allowable sustainable groundwater extraction rates. To be effective, however, popular mass action on a regional scale is required to cause significant improvement (Shah et al. 2003). Ideally, groundwater should be considered a storage reservoir to smooth fluctuations and allow flexible access, not a stock to be depleted.

6.4.4 Atmospheric Water Capture

Capturing water vapour from the atmosphere is an appealing concept that is receiving substantial popular attention. Numerous methods have been proposed to access atmospheric water, including cooling a surface below the dewpoint of the ambient air, concentrating water vapour through use of solid or liquid desiccants, and inducing convection in a tower structure (Wahlgren 2001). Several types of "air water generators" are commercially available to provide limited quantities of drinking water, powered by either grid electricity (Peters et al. 2013; Ecoloblue 2017) or solar power (Zero Mass Water 2017).

Although removing water from the atmosphere is technically possible, it is unlikely to scale as a significant source of water due to several fundamental physical challenges. First, the water vapour content per volume of air is very low (ranging from about 4 to 22 g/m^3 at different locations around the world), thus huge amounts of air must be handled to obtain significant water (Wahlgren 2001). In reliably windy areas this air movement may take advantage of natural winds, though in less windy regions there will be a need for mechanical fans.

The second challenge is that the latent heat of condensation of water is high, meaning that a large amount of heat energy is released when water vapour changes to liquid water (Miller 2003). In fact, the same amount of energy that must be input to change liquid water to vapour, will be output when the vapour changes to liquid water.

To capture any significant amount of water from the air, there must to be a way to reject large amounts of heat. To give a sense of scale, the latent heat released when vapour is condensed into 1 litre of liquid water, is enough to raise the temperature of 1 litre of liquid water by more than 500 degrees C.[12] Rejecting this amount of heat is not trivial, typically requiring active devices such as heat pumps.

Atmospheric water capture can be achieved with both active and passive devices. In general, active devices powered by concentrated energy sources (such as electricity) can drive processes like heat rejection and air movement at a high rate. Passive water capture devices that use natural energy gradients (like wind and sunlight) that are less concentrated and more diffuse, will proceed at slower rates.

To capture significant amounts of water, passive air capture devices will necessarily have large active surface areas to compensate for slow unit process rates. This typically results in a large land footprint, high capital investment, and/or fragility and risk of damage.

Furthermore, the efficiency of atmospheric moisture harvesting is highly weather and climate dependent, varying with temperature, humidity, pressure and other factors (Gido et al. 2016). Although the idea of using the atmosphere as a dependable year-round source of household water is attractive, in practice the water supplied by an atmospheric water generator would likely be highly seasonal.

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[12]However, the water would no longer be liquid if its temperature were raised by 500 degrees C, so better to say that the heat would raise the temperature of 500 litres of liquid water by 1 degree C.

6.5 Purify contaminated water

Water quality problems can be caused by chemical, physical, microbiological, or aesthetic issues. Here we discuss removing salt from water (6.5.1), killing biological pathogens (6.5.2), removing arsenic and fluoride from water (6.5.3), and removing diverse chemical contaminants from water (6.5.4).

6.5.1 Remove salt from water

Desalination is the process of making potable water from saline water sources, such as sea water or brackish water. The salt content of water is typically measured in milligrams of total dissolved solids (TDS) per litre of water. The salinity of ocean water averages 35,000 mg/L globally, varying from about 32,000 to 38,000 mg/L. Water is generally considered potable when it contains TDS less than about 1000 mg/L, though many potable water standards in Asia are lower than this. The Indian standard specifies an acceptable limit of 500 mg/L, though in the absence of an alternative source the permissible limit is 2000 mg/L (BIS 2012).

Desalination is currently used in select regions of the world. There are more than 7500 desalination facilities worldwide, over half of which are located in the Middle East (Shatat & Riffat 2014). Virtually all are powered by fossil fuels and are often integrated with, and use waste heat from, electricity generating stations. The world's largest desalination plant is located in Ras Al-Khair in Saudi Arabia, which produced over a million cubic meters of fresh water per day in 2014. In South Asia, desalination is used by industrial water users such as petroleum and petrochemical industries. The southern Indian city of Chennai gets about a quarter of its domestic water from two desalination plants, each producing about 100,000 m^3 per day, in operation since 2010 and 2013.

There are numerous desalination technologies, which can be divided into four major categories depending on the driving force of the process: thermal, pressure, electrical and chemical (Miller 2003; Youssef et al. 2014; Subramani & Jacangelo 2015).

In thermally driven systems, evaporation and condensation at different temperatures and pressures are the main processes used to separate salts from water. In these systems, heat transfer is used to either boil or freeze the feed water to convert it to vapor or ice, so the salts are separated from the water. The most common thermal processes include the multi-stage flash process and the multi-effects distillation process (Shatat & Riffat 2012). Other thermally activated systems include vapor compression distillation, humidification - dehumidification desalination, solar distillation and freezing.

Pressure-activated systems use a pressure gradient to force water through a permeable membrane, leaving salts behind. In recent decades, membrane technologies have matured and most new desalination installations use membranes. Of these, the reverse osmosis (RO) process is the most common; others include forward osmosis and nanofiltration.

Electrically-activated systems take advantage of the charged nature of salt ions in solution, by using an electric field to remove ions from water. The most common configuration is electrodialysis (ED), which currently accounts for about 4% of global desalinated water production. An emerging technology is capacitive deionization.

Chemically-activated desalination systems include ion-exchange desalination, liquid–liquid extraction and gas hydrate or other precipitation schemes. There are numerous alternate desalination processes that are technically possible but have economic or practical issues (Miller 2003).

A major difference between the various processes is the source of energy that drives the desalination process, e.g. heat, pressure, electrical or chemical (Rao et al. 2016). Cost of the energy supply strongly affects the cost of desalination. In general, thermal desalination uses large amounts of heat, reverse osmosis uses much smaller amounts of electricity, and electrodialysis uses even less electricity but is limited to low-salinity feed water (see Exhibit 76). The overall cost of the various processes also varies and is heavily dependent on scale. Larger facilities are far less expensive per cubic meter of fresh water (see Exhibit 77).

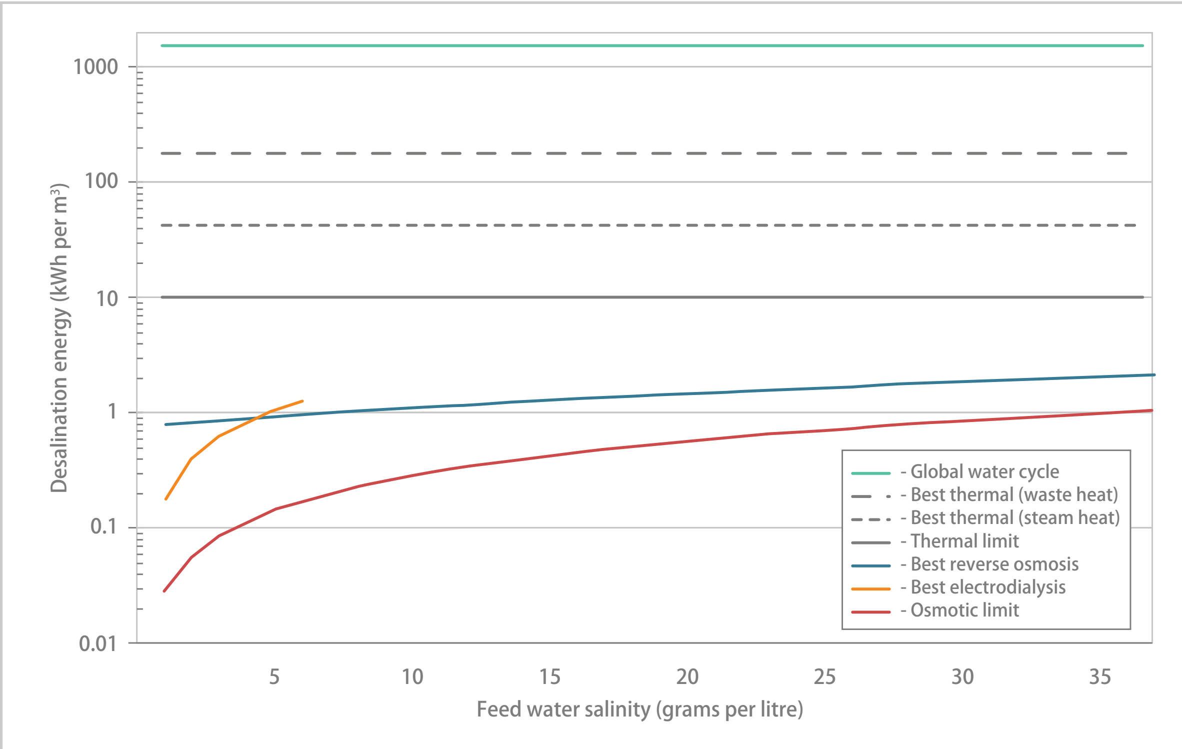

Exhibit 76. Energy use for desalination (kWh per m^3 of fresh water) as a function of feed water salinity (grams TDS per litre of feed water) for various desalination processes. Note vertical axis is logarithmic. (Source: ITT analysis based on Cerci et al. 2003, Fritzmann et al. 2007, Elimelech & Phillip 2011, Shatat & Riffat 2014)

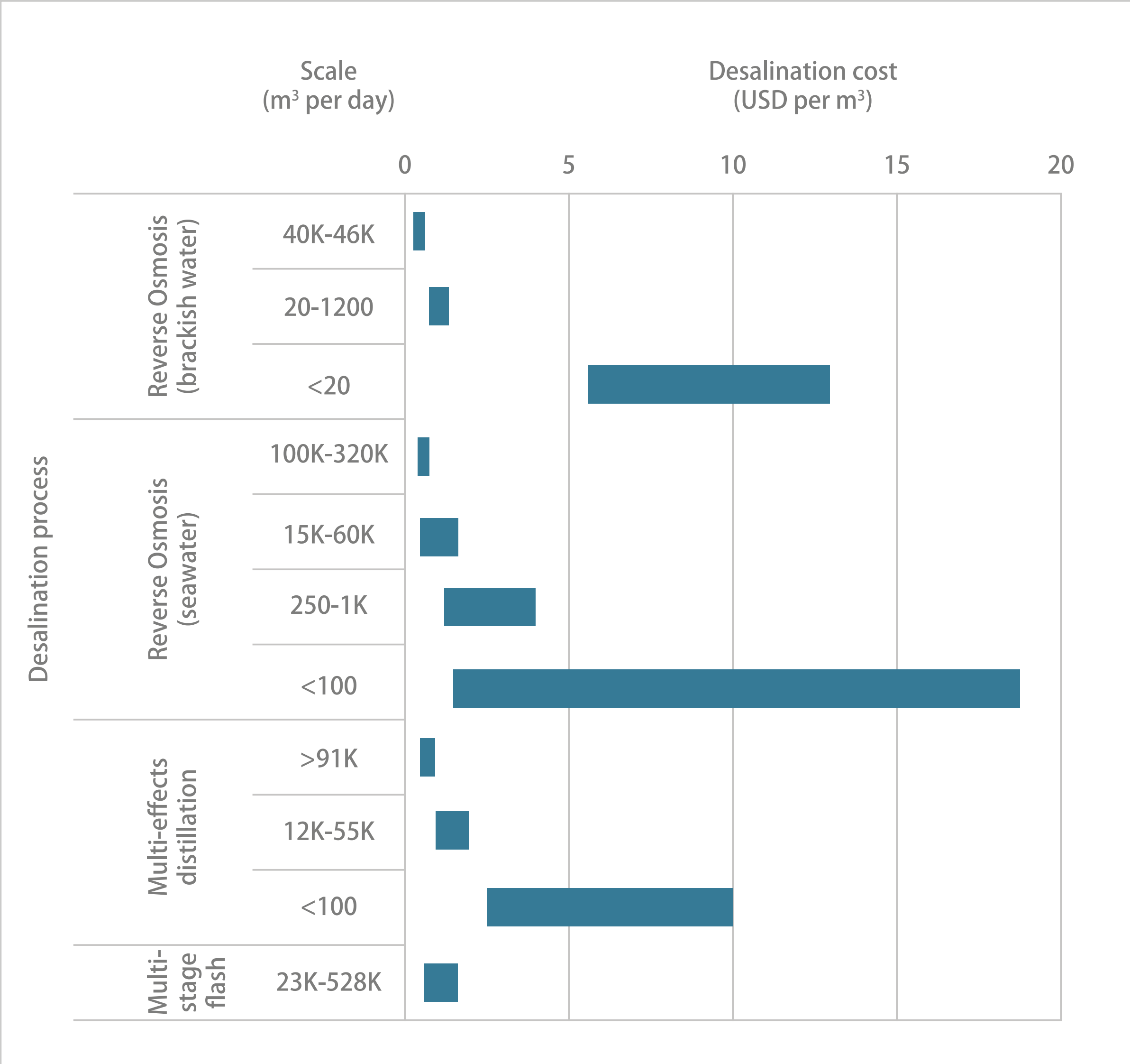

Exhibit 77. The levelized cost of current desalination processes (USD per m^3 of fresh water) varies depending on the technology used and the scale of the process (m^3 per day). The cost of energy inputs is also a significant variable. (Source: data from Shatat & Riffat 2014).

Membrane-based seawater desalination technologies have benefited from numerous improvements during recent decades, including higher-permeability membranes, installation of energy recovery devices, and the use of more efficient pumps. These technologies are approaching theoretical limits of energy efficiency (see Exhibit 78) and are already used at commercial scale for industrial and domestic use (Elimelech & Phillip 2011).

Although minor incremental efficiency improvements may still be gained, it is unlikely that major technology breakthroughs will fundamentally alter the seawater desalination landscape. DOE (2017) found that adoption of current state-of-the-art practice would reduce total energy use by 20% from current typical level, and opportunities from additional R&D could potentially reduce it by about half, before reaching a practical minimum level of energy use for seawater desalination.

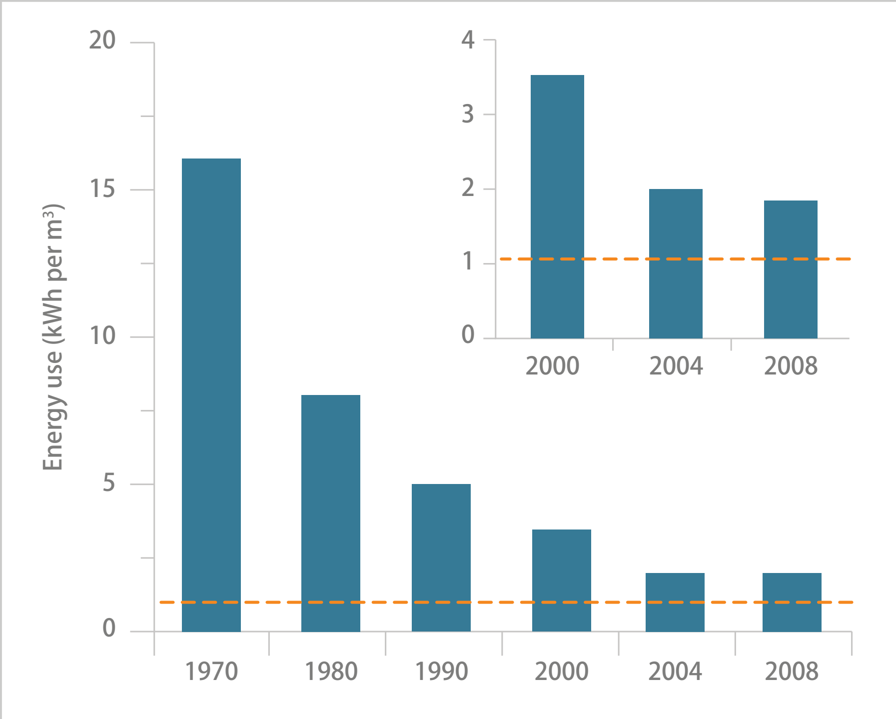

Exhibit 78. The energy requirement for seawater desalination using reverse osmosis has decreased during recent decades due to technology improvements. It is approaching theoretical limits of efficiency, shown by the dashed line (Source: data from Elimelech & Phillip 2011).

For brackish water, however, there are major opportunities for significant reductions in desalination cost and energy use, through innovative electrochemical or other emerging techniques. The minimum theoretical energy requirement for desalination varies with the salinity of the feed water-- less energy is fundamentally needed to desalinate brackish water, compared to seawater.

Conventional thermal or pressure-based desalination techniques require similar energy inputs regardless of the feed water salinity (although various configurations of brackish water reverse osmosis desalination are available to somewhat improve efficiency; see Li 2012). Electrically-driven techniques such as electrodialysis (ED) and capacitive deionization (CDI) are limited to low-salinity feed water, but potentially have much lower cost and energy use than pressure or thermal techniques (see Exhibit 76). ED and CDI are highly efficient for desalinating feedwater on the dilute end of the brackish water range (0.6-4 g/L TDS).

ED and CDI technologies use less energy because they transport the (relatively few) dissolved salt ions out of the feed water, rather than transporting the (plentiful) water molecules away from the salt as in thermal and pressure technologies (Suss et al. 2015). The electrical current required for ED and CDI is proportional to the amount of salt removed (Knust et al. 2014).

Electrically-driven desalination processes can achieve high water recovery and high brine concentrations. Electrical methods only remove ions from the water but leave organics and colloids in suspension, which is of concern for household water, but less important for irrigation water. They require little or no feedwater pre-treatment, and membrane fouling can be prevented by reversing the electrode polarities. However, the selection and configuration of membranes is highly dependent on feedwater chemistry, thus must be adapted to local conditions of feedwater composition and concentration.

CDI is an important emerging technology that separates ions from water by using two highly porous electrodes, such as carbon aerogels, to capacitively adsorb ions thereby removing them from solution. Once the ionic capacity of the electrodes becomes saturated, the polarity is reversed to release the ions, and the cycle is repeated. CDI is intrinsically a batch process that relies on polarity reversal, making it more difficult to implement in a continuous process. Another challenge of CDI is a limited cycle life due to corrosion of the positively charged electrode during operation. Activated carbon is the most commonly used electrode material.

Electrode materials for CDI must have low electrical resistivity, high specific surface area and controllable pore size distribution. Numerous electrode materials have been investigated such as activated carbons, alumina and silica nanocomposites, carbon nanotubes, carbon nanofibers, carbon aerogel, graphene and mesoporous carbon. There is also potential for improved performance due to doping effects and blending of different materials (AlMarzooqi et al. 2014).

There are additional opportunities to increase system efficiency and decrease delivered water costs for all desalination techniques, including brackish and seawater. These include optimising and standardising the full desalination system, including feed water input, pre-treatment, desalination, post-treatment, and brine disposal. There are also opportunities to make technological breakthroughs that minimize or eliminate membrane fouling, scaling, and general maintenance, which would reduce breakdowns and allow small scale systems to become more feasible. System characteristics should be tailored depending on scale and feed water salinity. There should also be a focus on determining the appropriate unit scale for various applications (e.g. household, village, city) and developing appropriate business models to ensure economic sustainability.

The challenge of brine disposal must also be addressed: a typical recovery ratio of current reverse osmosis desalination processes is 50%, meaning that for each m^3 of freshwater produced, one m^3 of concentrated brine waste is created and must be disposed of. Electrodialysis processes typically have higher recovery ratios, thus produce less brine waste by volume.

RO and other desalination technologies are already commercially available and in use for relatively high-value, low-volume requirements. These include drinking, cooking, washing and other domestic uses, and industrial water uses. Agricultural water use for conventional irrigation typically requires much larger volumes and much lower costs than desalination can feasibly provide. Absent a breakthrough that enables large scale, very low cost technologies, desalination is unlikely to be used as a water supply for extensive agriculture, due to the relatively high cost of desalination and the large volumes of irrigation water needed (see Exhibit 79).

Desalination may be more suitable for high intensity cultivation of high value crops, using techniques such as hydroponics or precision irrigation that have high water use efficiency. As additional efficiency gains are realized in large-scale brackish water desalination, these resources could enable greater use of desalinated water in agriculture. Kumar (2017) showed economic viability of desalinated water for irrigating high value fruits, vegetables, and flowers in water scarce regions of India that also have brackish groundwater that can be treated, such as northern Gujarat, western Rajasthan, and southwestern Punjab.

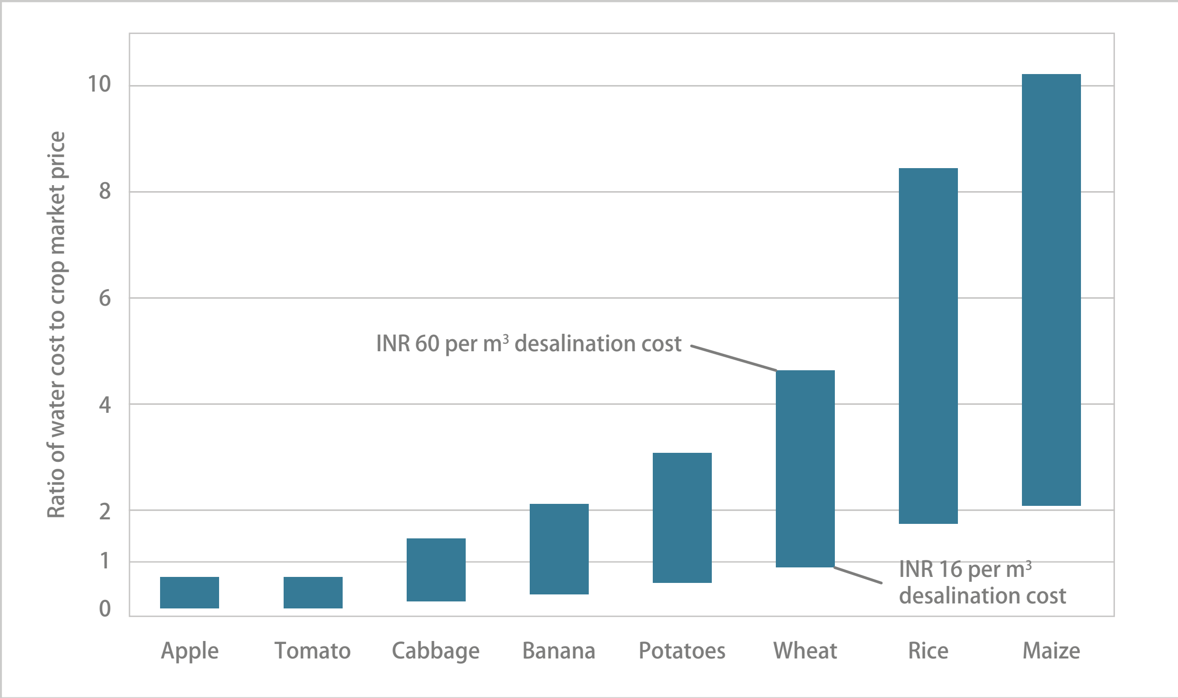

Exhibit 79. If desalinated water were used for conventional crop irrigation, the water cost would exceed the current consumer price of all cereals and most fruits and vegetables. Efficiently using desalinated brackish water to grow high-value crops may be more viable. (Source: ITT analysis based on crop irrigation water requirements from Fishman et al. 2015 and The Guardian 2013; average consumer crop prices in India from USDA 2017 and AgriXchange 2017; low desalination cost (INR 16 per m^3) of large-scale brackish water RO from Shatat & Riffat 2014; and typical desalination cost (INR 60 per m^3) representing current seawater RO in Chennai)

Though typically powered by grid electricity or fossil fuels, desalination can be done using renewable energy. Solar stills are simple devices that combine an evaporator that exposes feed water to sunlight and a condenser that converts the resulting vapour to liquid. Numerous designs for solar stills have been proposed, but few have balanced the competing needs for affordability, durability and efficiency (El-Bialy et al. 2016). A relevant metric when comparing direct solar desalination methods is the amount of fresh water produced per square metre of land area per day. Solar stills have a theoretical maximum efficiency of about 10 litres per m^2 per day.[13] Actual solar stills typically produce 3 to 5 litres per m^2 per day at efficiencies of less than 50%. Although ideas have been proposed to increase the efficiency of solar stills (e.g. Li et al. 2016), their additional cost and complexity may preclude widespread adoption. Another approach to solar desalination is to accept conventional efficiency levels of solar stills but aim for significantly reduced capital cost through innovative design and materials (e.g. Bhardwaj et al. 2016).

Solar desalination may also be achieved by using electricity from a photovoltaic (PV) solar array to power a RO desalination unit. This could produce about 500 litres per day per m^2 of land area[14] or 50 times the theoretical maximum output of a solar still. If the feed water is brackish, coupling PV power to electrodialysis desalination could produce even more fresh water per m^2 of land area (Wright & Winter 2014)

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[13]Theoretical limit of solar still based on solar insolation in sunny location of ~6.5 kWh per m^2 per day, and latent heat of water evaporation of 0.63 kWh per kg, resulting in maximum water evaporation of ~10 kg per m^2 per day.
[14]RO desalination powered by PV electricity based on solar insolation in sunny location of ~6.5 kWh per m^2 per day, PV solar-to-electricity conversion efficiency of 20%, and RO specific electricity use of 2.5 kWh/m^3, resulting in fresh water production of ~500 litres per m^2 of PV panel per day.

6.5.2 Kill biological pathogens

Microbial pathogens in water must be killed, deactivated, or physically removed before the water can be safely consumed. There are numerous ways that this can be achieved at various scales, including chemical, thermal, radiation and filtration methods (see Table 7).

Approach	Process	Appropriate scale	Observations
Chemical	Chlorine	All scales	May produce disinfection by-products; turbidity can inhibit effectiveness
	Zinc	Household	Requires removal of precipitated material
	Iodine	Household and community	May produce disinfection by-products
	Ozone	Municipal	May produce disinfection by-products
	Silver and copper nanoparticles (e.g. MadiDrop)	Household	Silver is readily absorbed by the body, but it is unclear whether it causes long -term harm; does not form disinfection by-products
	Combined coagulation (e.g. PuR)	Household	Simple technology, but requires constant input of chemicals
Thermal	Boiling	All scales	Energy intensive
Ultraviolet (UV) Radiation	Solar disinfection (e.g. SODIS)	Household	Turbidity and cloud cover can inhibit effectiveness
	UV Waterworks	Household and community	Turbidity can inhibit effectiveness
Filtration	Membrane filter (e.g. reverse osmosis)	All scales	Removes pathogens and many inorganic contaminants
	Ceramic pot	Household	Low cost
	Rapid sand filter (larger particles) and Slow sand filters (drinking water quality)	Community and municipal	Rapid sand filters can be used as pre-treatment step followed by chlorine, ozone, etc.
	Pressure filters	Municipal	May require pre-treatment (i.e. settling or pre-filtration)

Table 7. Numerous methods are available to kill or remove pathogens from drinking water. (Source: based on Gadgil 1998; Fewtrell 2014; Amrose et al. 2015; USEPA 2018)

Many of these technologies are combined together to achieve better drinking water quality. For example, ceramic filters can be lined with silver and copper nanoparticles to ensure all pathogens are killed and filtered out. Another example is chloramination, which is the combined use of chlorine dioxide and UV radiation. Chlorine is the most widely used water disinfectant, and ozone is the second most widely used.

Chemicals used as disinfectants will sometimes react with naturally occurring chemicals in a water source to produce by-products that are harmful to human health. Some common by-products are bromate, chlorite, haloacetic acids, and trihalomethanes. Many of these by-products are toxic and/or carcinogenic (USEPA 2018). Activated carbon filters may be used secondarily to adsorb and remove some of these by-products.

Water quality testing is carried out to ensure that drinking water is safe. The basic WHO drinking water guideline is that no *E. coli* should be detected in a 100 mL sample. Other microbes and indicators can be used to assess water safety (see Table 8). It is important to note that these refer to established "textbook" methods, which may be difficult to successfully implement in South Asia due to various challenges. For example, intermittent treated water supply (detailed in Section 6.2.1) can create pressure gradients that result in contaminated delivered water. Furthermore, water sources that are treated onsite (i.e. point-of-use treatment) can become contaminated in the household from unhygienic storage or incorrect handling.

Contaminant	Potential Health Effects	Sources of Contamination
Cryptosporidium	Gastrointestinal illness (e.g. diarrhoea and vomiting)	Human and animal faeces
Giardia lamblia	Gastrointestinal illness (e.g. diarrhoea and vomiting)	Human and animal faeces
Viruses (enteric)	Gastrointestinal illness (e.g. diarrhoea and vomiting)	Human and animal faeces
Legionella	Legionnaire's Disease, a type of pneumonia	Occurs naturally in water; multiplies in heating systems
Total Coliforms	Not a health threat, but used to indicate if other potentially harmful bacteria may be present	Occur naturally in the environment as well as in faeces
Heterotrophic plate count (HPC)	No health effects. HPC is an analytic method used to measure variety of bacteria in a water sample	HPC measures bacteria that are naturally present in water
Turbidity	Measure of the cloudiness of water; used to indicate water quality and filtration effectiveness. Higher turbidity levels are associated with higher concentrations of pathogens	Soil runoff

Table 8. Water can be analysed for the presence of microbial contaminants and for other quality indicators to determine its suitability for drinking. (Source: adapted from USEPA 2018)

6.5.3. Remove arsenic and fluoride from water

Arsenic is a naturally occurring element that is present in some groundwater, as detailed in Section 3.5. WHO and USEPA both specify that no more than 10 µg/L (10 ppb) of arsenic should be present in drinking water. The national standard practised in Bangladesh limits arsenic to 50 µg/L. See Section 3.5 for more details.

The most common current arsenic removal technologies can be grouped into five categories: oxidation, ion exchange, activated alumina, membrane, and coagulation/co-precipitation/adsorption (Rahman & Al-Muyeed 2009). Some promising technologies, such as electrocoagulation, are emerging. Each of these technologies has trade-offs in terms of water characteristics (i.e. pH, concentrations of arsenic, iron, phosphate, silicate, and calcium), operation and maintenance complexity, and aesthetic water quality. Most arsenic-removal technologies are available at the community- and household-level. Community-level treatment typically exists as column filters containing the media (i.e. activated alumina, granular ferric hydroxide, or hybrid anion exchange).

The most widely used household arsenic removal systems use zerovalent iron, such as the SONO filter. However, many household users complain of low flow rate and occasional clogging. In terms of effectiveness, oxidation-filtration and ion exchange technologies have shown poor efficacy, while zerovalent iron and other adsorption technologies work well. Coagulation-coprecipitation-filtration technologies receive mixed reviews from users (Amrose et al. 2015).

Despite the popularity of reverse osmosis (RO) for removing other water contaminants, conventional RO only partially removes arsenic because of the small size of arsenic ions relative to salt ions. It would be possible, in principle, to pass the water through the RO membrane multiple times to remove more arsenic. However, achieving the very low concentration required for arsenic (10 μg/L) would make the cost prohibitively high.

A major concern regarding arsenic removal technologies is that the collected arsenic must be disposed of after it has been removed from a water source. Unfortunately, this disposal practice is often unregulated, and arsenic waste is sometimes dumped in ponds or open fields. The arsenic concentration of these wastes ranges from 0.1 to 7500 mg/kg (Amrose et al. 2015).

Several arsenic mitigation interventions have been studied in recent years to assess their feasibility from technological, institutional, and community-adoption perspectives. Overwhelmingly, it was found that borewells are the waters source of choice among communities, even if their contamination status is unknown (Inauen et al. 2013; Johnston et al. 2014; Hossain et al. 2015). In Bangladesh, arsenic levels in groundwater are typically stratified, with low concentrations near the shallow water table, maximum concentrations typically 20-40 m below ground, and very low concentrations deeper than about 100 m (Ravenscroft et al. 2005). Aquifers that are 100-200 m deep thus offer safe water in the near- to medium-term, but are susceptible to long-term downward arsenic intrusion with intense groundwater pumping.

Fluoride is another naturally occurring element that is present in some groundwater, as detailed in Section 3.5. WHO specifies a preferable fluoride concentration in drinking water of less than 0.5 mg/L and a maximum concentration of 1.5 mg/L (Mumtaz et al. 2017). Various defluoridation techniques have been developed, including coagulation, adsorption, ion-exchange, electrochemical, and membrane-based methods.

The coagulation technique uses reagents such as aluminium salts, lime, calcium and magnesium salts, poly aluminium chloride, and alum to precipitate fluoride through a chemical reaction, in which the precipitated fluoride coagulates and can then be removed. These chemical processes include coprecipitation, in which fluoride is simultaneously precipitated with a macro-component through crystal formation, adsorption, occlusion, or mechanical entrapment. The Nalgonda technique (see Exhibit 80) is a coagulation-defluoridation technique that has seen limited acceptance because it is relatively difficult to maintain and operate. This is a common problem with defluoridation technologies.

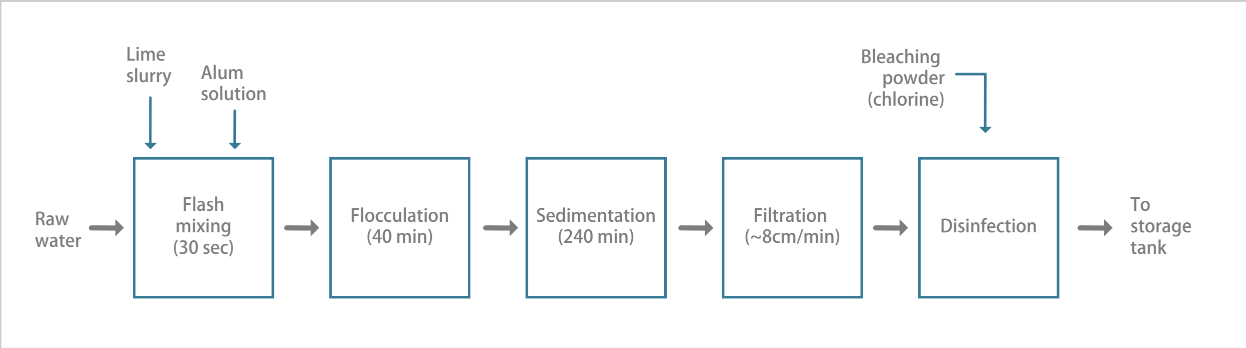

Exhibit 80. Process steps involved in the Nalgonda technique for removing fluoride from drinking water. (Source: adapted from Ayoob et al. 2008)

Adsorption processes involve continuously cycling fluoride-contaminated water through columns containing an adsorbent, such as bone char, activated alumina, activated carbon, activated bauxite, ion-exchange resins, fly ash, super phosphate and tricalcium phosphate, clays and soils, synthetic zeolites, and other adsorbent minerals. The cyclic sorption tends to aggregate and concentrate the fluoride, which can then be disposed of safely.

Electrochemical processes include electrocoagulation and electrosorptive techniques. During electrocoagulation processes, Al^{3+} ions are released from aluminium electrodes through an anodic reaction, which generate aluminium hydroxides that adsorb fluoride ions near the electrodes, resulting in a fluoride complex that can then be easily removed. Electroadsorptive techniques only differ from adsorption techniques in that an electric field is applied to the adsorbent bed, which increases its adsorption capability.

The use of membrane technologies in defluoridation is relatively new and includes reverse osmosis, nano- and ultrafiltration, electrodialysis, and Donnan dialysis. These processes typically have high operational costs compared to other defluoridation techniques (Ayoob et al. 2008, Mumtaz et al. 2015). Table 9 provides an overview of common techniques to remove fluoride from drinking water and summarizes their advantages and limitations.

Fluoride removal technique	Stage of Development	Advantages	Disadvantages
Coagulation: Precipitation and Coprecipitation			
Precipitation by calcium oxide	Established and most commonly used technology	Cheapest technology	High sludge production; high pH of treated water; precipitate settles poorly; high F concentration in effluent
Precipitation by magnesium oxide	Established	Affordable	High sludge production; high pH of treated water
Precipitation by calcium chloride and monosodium phosphate	Emerging technology	Reliable operating cost; no health risk in case of over dosage of reagents	Too short contact times increase the escape of chemicals in the treated water. Long contact time may result in precipitation of calcium phosphates in the upper parts of the filter bed. Both these actions will reduce the removal efficiency
Coprecipitation by alum	Well-known and established technique; widely used	Chemicals readily available; affordable	Low pH of treated water; high dose requirements for higher fluoride concentrations increases cost; expected presence of sulphate and aluminium concentrations in treated water especially at high pH; sludge disposal is a problem
Coprecipitation by alum and lime (Nalgonda)	Well-known and established technique; widely used	Chemicals readily available; affordable	Difficult to control dosages for different sources of raw water with varying alkalinity and fluoride concentration; hardness and pH of the treated water are high; potential high concentrations of sulphate ions and/or residual aluminium in treated water can harm human health; sludge disposal is a problem; requires skilled operation
Adsorption/Ion Exchange			
Bone	Established	Can reduce F to low concentrations	Treated water tastes like bone; limited social acceptance
Bone char	Well-known and established	Can reduce F to low concentrations; local availability and processing facilities	Capacity reduces drastically after successive regenerations; more expensive than coagulation techniques; may not be culturally or socially acceptable
Clays	Established	Economical	Defluoridation potential is generally low; regeneration is very difficult; can result in high concentrations of $Al^{3}+$, $Fe^{3}+$, and silica in treated water
Activated alumina	Very well established	High F removal capacity; minimum interference from counter-ions with consistent potential; versatile applications	Costly compared to coagulation processes and bone char; high pH reduces potential; only works effectively within the range of pH 5-7; has potential to be colonised by microorganisms; not effective at TDS 1500 mg/L

Fluoride removal technique	Stage of Development	Advantages	Disadvantages
Membrane			
Reverse osmosis	Well established and studied	Immense commercial applications; organics and salts also removed; high F removal capacity	Sensitive to polarisation phenomenon; chances of biological and mineral fouling; treated water may lack the right balance of minerals; poor water recoveries; high cost; turbidity interferes with effectiveness
Nanofiltration	Well-accepted membrane separation process	Handles higher water fluxes at lower transmembrane pressures than RO	More sensitive than RO to pH and ionic strength; leaves large concentrations of retentate fraction; high cost; requires skilled operators
Electrodialysis	Established	Can be used for simultaneous defluoridation and desalination; commercially established; more economical than RO; more resistant to fouling.	Requires high degree of pre-treatment; ineffective in removing low molecular-mass non-charged compounds; membrane scaling; treated water quality is inferior to that of RO; skilled operator required; high cost
Donnan dialysis	Relatively new	Similar to electrodialysis	Operation requires addition of a driving counter-ion to stripping solution; reduced efficiency in high-saline waters; high cost; requires skilled operation; turbidity interferes with effectiveness
Electrochemical			
Electro-coagulation	Emerging technology	Very high efficiency compared to traditional coagulation; also reduces concentrations of bacteria, hardness and nitrate; technically simple	Interference from other anions like sulphate; need for regular replacement of sacrificial electrodes; high energy costs
Electrosorption	Emerging technology	High efficiency; excellent regeneration potential	Costly due to high consumption of electric power

Table 8. Methods of removing fluoride from water. (Source: adapted from Ayoob et al. 2008 and Mumtaz et al. 2015)

6.5.4 Remove chemical contaminates

A diverse range of chemical contaminants can be found in South Asian waters. Agricultural sector contaminants primarily come from run-off water containing fertiliser (nitrogen and phosphorous) and pesticide (insecticide, herbicide, fungicide) residues. Industrial contaminants span a wide range, from heavy metals discharged from mining, smelting and e-waste recycling industries, to high organic loading released from pulp/paper, animal processing and pharmaceutical industries. The petroleum, petrochemical and transport industries are responsible for toxic compounds such as hydrocarbons, polychlorinated biphenyls (PCBs), persistent organic pollutants (POPs), volatile organic compounds (VOCs), and chlorinated solvents.

The primary agricultural sources of water pollution are nitrogen and phosphorous fertilisers. Phosphorus in water is not considered to be directly harmful to humans and animals, and no drinking water standards have been established for phosphorous (Carpenter et al. 1998). Toxicity caused by phosphorous in freshwaters is indirect, due to toxic algal blooms or anoxic conditions stimulated by phosphorous pollution. Nitrogen pollution, however, poses a direct health threat when in the form of nitrate (NO_3). High levels of nitrate in drinking water have been linked to methemoglobinemia in infants, various cancers in adults, and toxic effects on livestock (Carpenter et al. 1998, Richard et al. 2014, Schullehner et al. 2018).

Across this diversity of contaminants, there exists a range of technological processes to remove them from water. These include adsorption, filtration, electrochemical removal, chemical reaction, precipitation, bioremediation and others. Adsorption is the most commonly used water treatment method for removing chemical contaminants since it is effective at removing a wide range of chemicals from water and can be operated relatively inexpensively. Small-scale household water purification systems typically contain an activated carbon component, which effectively adsorbs many organic chemical contaminants such as chlorine, VOCs, insecticides and herbicides. However, it does not remove microbial contaminants or many inorganic materials.

Another advantage of adsorption is that many waste materials with high carbon or oxygen contents can be used as precursors to the technology, including coconut shells, scrap tyres, fruit waste, tree bark and other tannin-rich materials, sawdust, rice husk, fly ash, seaweed, and seafood processing wastes. These waste materials must first be carbonised below 800 °C in an anaerobic setting, and then they can be activated at high temperatures using an oxidant such as air, steam, or carbon dioxide (Ali et al. 2012). Adsorption precursors are most effective at removing chemical contaminants when they have high thermal stability, high abrasion resistance, and small pore diameter which results in greater surface area.

Different chemical contaminants require specific removal techniques. For example, PCBs can be effectively removed with biological activated carbon, while atrazine adheres well to fibre glass activated carbon. Additionally, commercially-available granular activated carbon can be coated in various catalysts and chemicals to remove other diverse chemicals (Goel et al. 2005). Heavy metals within a defined concentration range can be effectively removed with adsorbents made from low-cost agricultural by-product materials (Hegazi 2013).

Adsorbents work best at purifying wastewater with a high concentration of chemical contaminants, which can make it difficult to remove low levels of contaminants in natural waters given the high degree of dilution (Ali et al. 2012). Regardless of the treatment method, there is the added challenge of disposing or containing the removed contaminants. Currently, there is no standard or recommended way to dispose of removed contaminants to eliminate re-exposure. Generally, removal of many chemical contaminants from water is extremely challenging and costly, thus best practice is typically to increase safeguards to avoid or minimise their uncontrolled discharge to the environment. This is discussed in more detail in Section 6.7.2.

6.6 Identify, access and extract groundwater

Although over-extraction of groundwater is a problem in many regions of South Asia (as described in Sections 3.2 and 3.3), other regions of South Asia possess abundant groundwater yet their populations face economic water scarcity (described in Section 3.12). Groundwater mapping may assist in all regions, to better understand and manage groundwater resources. Improved methods to make affordable wells may assist in regions facing economic water scarcity. Improved groundwater pumping methods may assist in all regions, particularly those with low-income populations and deepening water tables. These issues are discussed here.

6.6.1 Groundwater mapping

The goal of groundwater mapping is to understand the hydrogeological landscape, to inform better management of groundwater resources. Comprehensive groundwater mapping can be used to determine the location and quality of groundwater, as well as aquifer recharge mechanisms that affect the sustainable quantities of groundwater available for extraction and use. The focus of groundwater mapping is on the mechanisms of sustainable groundwater cycling, to facilitate long-term utilisation and enhancement (through e.g. managed aquifer recharge) of sustainable groundwater resources. It may also be used to temporarily increase water supply by enabling the precise siting and one-time extraction of remaining fossil water aquifers. India has conducted pilot groundwater mapping studies in six areas with different hydrogeological terrains (CGWB 2015c), with intentions to map the entire country.

A range of techniques can be used to provide primary data for groundwater mapping (Klee et al. 2015). Data is gathered across many scales, from in situ underground sampling, to surface-based sensing techniques, to remote sensing from aircraft or satellites. Multiple techniques are commonly used in parallel to combine information on different characteristics, to generate more robust maps. Several data-gathering techniques have been developed based on acoustic, electric or electromagnetic principles, to provide data on geological structures, surface morphology and their hydrologic characteristics:

- Seismic surveys are made by propagating acoustic energy through the ground, and tracking seismic refraction of compressional waves which show increasing velocity with density. Seismic surveys provide information on the internal structure of aquifers such as clay and silt layers that limit the overall vertical permeability.

- Electrical resistivity techniques (such as electrical resistivity tomography, ERT) induce an electrical current in the ground, and the resulting electrical potential at different locations is used to measure the variation in ground conductivity, or its inverse, resistivity. Different materials, and the fluids within them, will show different abilities to conduct an electric current. Electrical resistivity methods are often used for well siting and for locating suitable sites for percolation tanks in hard rock areas.

- Ground penetrating radar (GPR) emits high-frequency electromagnetic waves into the ground, and receives and interprets the microwave energy reflected back to the surface from different underground materials, to provide detailed subsurface cross sections.

- Airborne transient electromagnetic (ATEM) systems are used to map the apparent conductivity of the ground. These can be fitted to helicopters or fixed-wing aircraft.

- Time domain electromagnetics (TDEM) methods can map the shallow subsurface, but are susceptible to interference from pipelines and power lines. In this method, current pulses are sent through a large square wire loop on the ground. The decay of current at the end of each pulse generates a magnetic field that enters the ground. Eddy currents induced by this changing magnetic field generate secondary magnetic fields in the ground. The amplitude and rate of decay of these secondary fields are measured at the surface and analysed to determine underground characteristics.

- Frequency domain electromagnetics (FDEM) are typically used to measure variations in lateral conductivity along linear or gridded profiles.

Another valuable source of primary groundwater data is direct surveys of existing wells to determine the quality of groundwater as well as the depth and fluctuation of the water table. This is typically done manually (if at all), providing only intermittent data points. A potentially important tool for future management of South Asian groundwater is a distributed network of digital sensors to provide real-time monitoring of well water characteristics throughout the region. Hydrogeological data from multiple sources could then be integrated to form the basis of a user-friendly online map of real-time groundwater quality and quantity. Implementation of such a network will require the development of lower cost and more robust instrumentation.

6.6.2 Well drilling

Groundwater well drilling is an important part of water supply development in South Asia, and played a major role in the Green Revolution. Many millions of borewells have been drilled in South Asia since the 1960s, and strong local expertise has been developed in siting and drilling wells, as well as in producing and maintaining drilling equipment. There is a variety of drilling technologies available, depending on soil characteristics and required depth (see Table 10).

Geological conditions		Percussion drilling	Hand-auger drilling	Jetting	Sludging	Rotary percussion drilling	Rotary drilling with flush	Air lift reverse circulation
Gravel	Unconsolidated formations	✓?	✗	✗		✓?	✗	✓
Sand		✓?	✓	✓	✓	✓?	✓	✓
Silt		✓?	✓	✓	✓	✓?	✓	✓
Clay		✓slow	✓	?	✓	✓slow	✓	✓
Sand with pebbles or boulders		✓?	✗	✗	✗	✓?	✗	?
Shale	Low to medium -strength formations	✓	✗	✗	✗	✓slow	✓	✗
Sandstone		✓	✗	✗	✗	✓	✓	✗
Limestone	Medium to high-strength formations	✓slow	✗	✗	✗	✓	✓slow	✗
Igneous (granite, basalt)		✓slow	✗	✗	✗	✓	✗	✗
Metamorphic (slate, gneiss)		✓v slow	✗	✗	✗	✓	✗	✗
Rocks with fractures or voids		✓	✗	✗	✗	✓	?	✗
Above water table		✓	✓	?	✗	✓	✓	✓
Below water table		✓	✗	✓	✓	✓	✓	✓

✓ - Suitable drilling method ✓? - Danger of hole collapsing ? - Possible problems ✗ - Inappropriate method of drilling

Table 10. Various well drilling technologies have been developed, which can create borewells in different geological conditions. (Source: adapted from WEDC 1994)

Well drilling in South Asia is typically done with portable diesel-powered rigs, such as percussion and rotary percussion methods. Powered mechanical rigs are expensive and have limited mobility to reach remote areas. They are able to effectively drill through most geological features and are relatively quick to drill a well. Numerous manual drilling techniques have been developed, which can produce borewells with less cost, and in locations that would be inaccessible to mechanical drilling rigs (see Exhibit 81). These manual techniques often involve community participation as drilling labour. Manual techniques are, however, slow and are limited in the geological strata they can drill.

Most current well drilling technologies suffer from high cost, limited portability, slow drilling rate, or limited geologic suitability. To expand groundwater opportunities to rural populations facing economic water scarcity, a drilling technology is needed that combines the speed and capability of powered equipment with the portability and low cost of manual techniques. Such a technology, such as the innovative air-lift reverse circulation drill recently introduced in India by ITT, could enable more accessible borewells in regions suffering from economic water scarcity such as Odisha, Assam and Bihar.

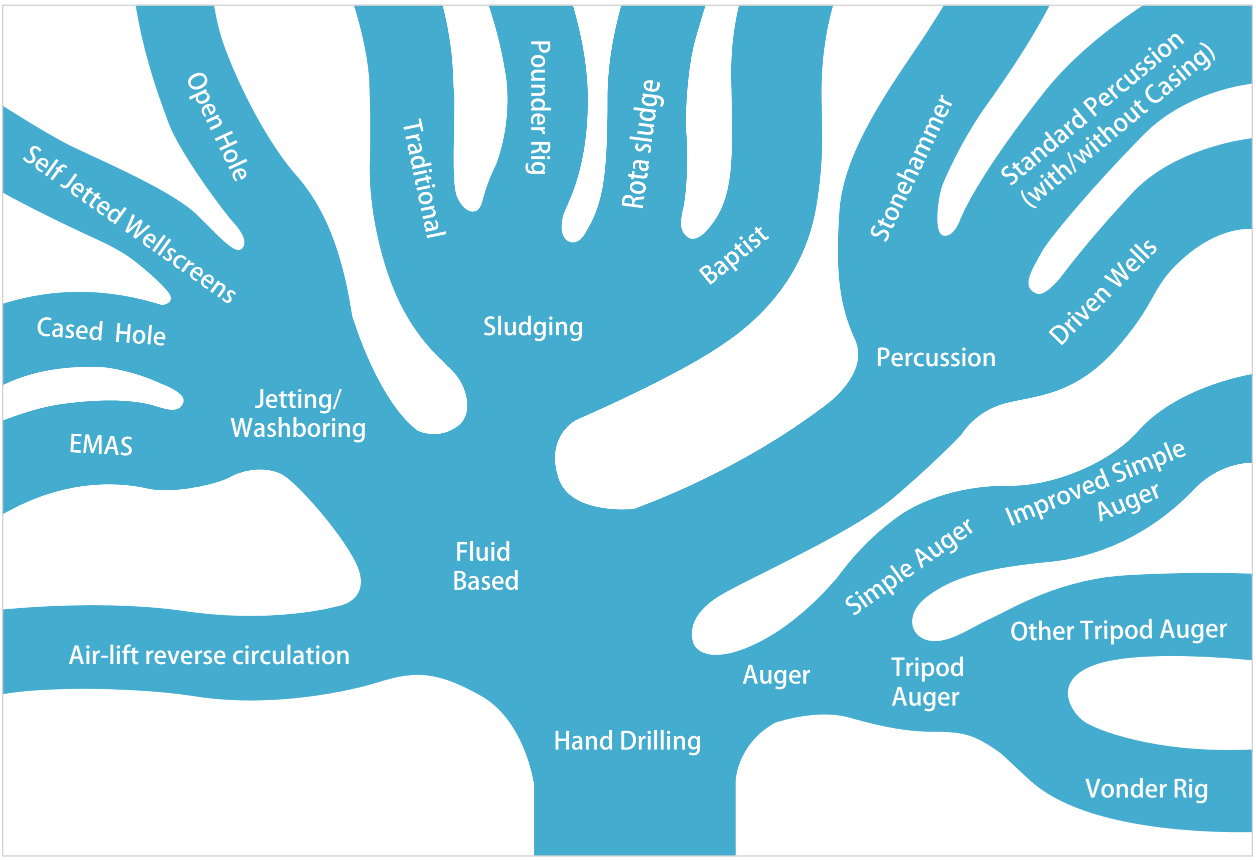

Exhibit 81. Numerous techniques have been developed for manual well drilling. (Source: adapted from RWSN 2009)

6.6.3 Water pumping

There is a broad range of water pumping technology, which can be categorised in various ways. One important distinction is based on pumping depth: shallow or deep. The divide occurs at a depth of about 10 metres, which is the longest column of water that can be drawn up a pipe. Shallow pumps are located at the surface, and "pull" water up from the well. Beyond 10 m of depth, deep well pumps must be used. These pumps are inserted into a well, and "push" the water up to the surface. Some form of power must be transferred from the surface down to operate the pump. This transfer takes the form of reciprocating metal rods in most handpumps, rotating shafts in line shaft pumps, and electrical current in submersible electric pumps.

Another important pump distinction is based on the source of motive power: human muscles or externally powered. Manual-powered pumps are commonly used to lift water from boreholes and shallow wells for household use in rural areas of South Asia. Technologies for shallow and deep handpumps were significantly advanced during the International Drinking Water Decade, 1981–90.

Robust community-scale handpumps such as the India Mark III and the Afridev were designed and widely deployed, with attention not only to technical efficiency but also user ergonomics and practical maintenance. Another advancement in manual pumping is the treadle pump, developed in Bangladesh during the 1970s and 80s. This low-cost shallow pump is actuated by strong leg muscles, and pumps sufficient water for irrigating smallholder farms. While marginal improvements may be made to manual pumping technology, no radical innovations are expected. Rather, improvements may be made by increasing coverage and ensuring maintenance and repairs.

Most irrigation pumps in South Asia are powered by an external energy source, usually grid electricity or diesel fuel. Electrical pump sets are common in much of India, while diesel-powered pump sets are more common in Pakistan, Bangladesh and eastern India (see Exhibit 82). A study of efficiency of electrical pump sets in Haryana found an average efficiency of 24% (World Bank 2001), while other studies of South Asia suggest average pump efficiencies of about 30% (Singh 2009; Kaur et al. 2016).

These efficiency levels are much lower than typical pump set efficiencies of >50% in industrialised countries, and well below the practical efficiency limit of about 85%. In South Asia, efficiencies can be increased by matching the size of pumps and motors to their tasks, as most pump sets in South Asia are oversized. Renovation of existing pump sets may gain efficiency by replacing foot valves and suction and delivery piping to reduce frictional losses. Currently, however, generous subsidies on pumping electricity discourage the adoption of more efficient pumping techniques or more rational irrigation water use (Singh 2012).

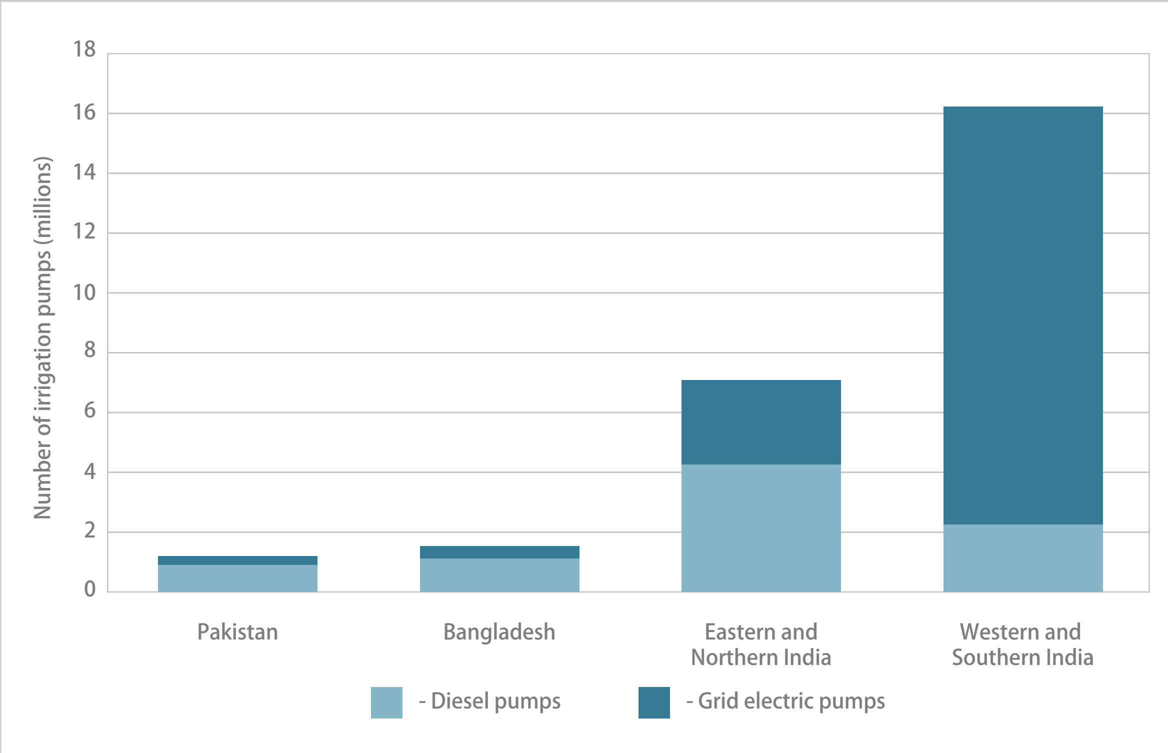

Exhibit 82. Diesel powered irrigation pumps are most common in Pakistan, Bangladesh and eastern and northern India (here defined as Assam, West Bengal, Bihar, Odisha, Jharkhand, Uttar Pradesh and Uttarakhand). Grid electric powered irrigation pumps are most common in western and southern India (here defined as Andhra Pradesh, Gujarat, Haryana, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Punjab, Rajasthan and Tamil Nadu). (Source: based on 2001-2005 data from Shah 2009, updated by ITT to year 2017 with estimated growth rates based on Siddiqi & Wescoat 2013, Shamsudduha 2013, KPMG 2014, India Ministry of Agriculture 2016)

Solar powered electric pump sets are under development, which use photovoltaic (PV) arrays to convert sunlight to electricity that then powers submersible or surface-mounted electric pumps (GIZ 2013). The number of PV pumps, and the land area they irrigate, is still small in South Asia and globally. Roughly 15,000 solar irrigation pumps have been installed in India, mainly in the states of Punjab, Rajasthan and Haryana (KPMG 2014). The technology nevertheless has the potential to significantly scale up in future, as part of a long-term transition toward renewable energy sources.

Direct solar pumping can be quite efficient, as all harvested power is used for pumping, and there is no need for batteries and associated losses. Modern positive displacement pumps have efficiencies of up to 70% (GIZ 2013). There is also potential for solar pumping to be integrated into village-level solar-powered mini-grid systems. Such integration may bring advantages to the farmer (e.g. the high capital cost of PV system is spread across many users) as well as to the mini-grid utility (e.g. having flexible and reliable pumping loads). However, the economic value of pumped irrigation water, expressed as willingness to pay by mini-grid users, is likely to be much less than that of competing uses of limited electrical power by households and industry.

There are significant barriers to the scale-up of PV-powered irrigation pumps including the high upfront cost of PV systems which are typically 10 times that of conventional pumps (KPMG 2014). This cost difference is diminishing over time as PV system costs decline. Other challenges include the present lack of maintenance skills and services, low awareness of PV pumps among farmers, and the risk of theft (Bassi 2018). Furthermore, since there is zero marginal cost for additional water pumping, there is a risk of unrestrained aquifer depletion if the technology is scaled up in the absence of rational water allocation systems.

Despite the very low operating costs of PV irrigation pumps, the high capital cost leads to long economic payback times, unless substantial subsidies (~80%) are offered by government (KPMG 2014). Economic payback periods for solar pumping systems in South Asia range from 0 to 14 years on subsidised prices, and from 6 to 25 years on non-subsidised prices (FAO 2018). Experience in both Bihar (GIZ 2013) and Rajasthan (Kishore et al. 2014) shows that wealthier farmers are better positioned to take advantage of subsidies on PV pumps, suggesting that the existing technology is more suitable for economic development of commercial farmers, rather than alleviation of economic water scarcity among poor subsistence farmers.

Several technology levers aim to integrate multiple aspects of the water system, to increase whole-system efficiency.

6.7 Eliminate pollution sources

While Section 6.5 focused on purification of contaminated water deals with the after-the-fact consequences of water pollution, this section focuses on proactive methods to avoid the sources of pollution.

6.7.1 Faecal waste management

The goal of faecal waste management is to contain faecal matter and associated wastewater, treat it, and then safely reuse or dispose of the residues. It is essential for the public health of a region that faeces are contained safely and disposed of properly. Prevention and reduction of faecal pollution at the source is the most imperative step and should be given priority. It is both more difficult and costlier to remove pollution from water bodies than it is to prevent it from entering.

Faecal waste management is one of the many necessary steps in improving the water security and public health of a region. These issues are closely intertwined and require a holistic set of interventions. The three-pronged approach of sanitation, clean water supply, and hygiene is increasingly seen as the solution to improving water quality and public health. Exhibit 83 illustrates the relationship between these three avenues - sanitation, water supply, and hygiene - and the various pathways of disease transmission.

Specifically, drinking water is contaminated at three main points: the source, in transit (i.e. through pipes), and in the home through improper storage. Food becomes contaminated in farm fields when open defecation occurs in fields, when farmers irrigate with wastewater, in markets due to unhygienic conditions, and in the home when the food comes into contact with contaminated hands or flies. Thus, faecal waste management is one of three important interventions required to prevent the spread of disease originating from faecal pathogens.

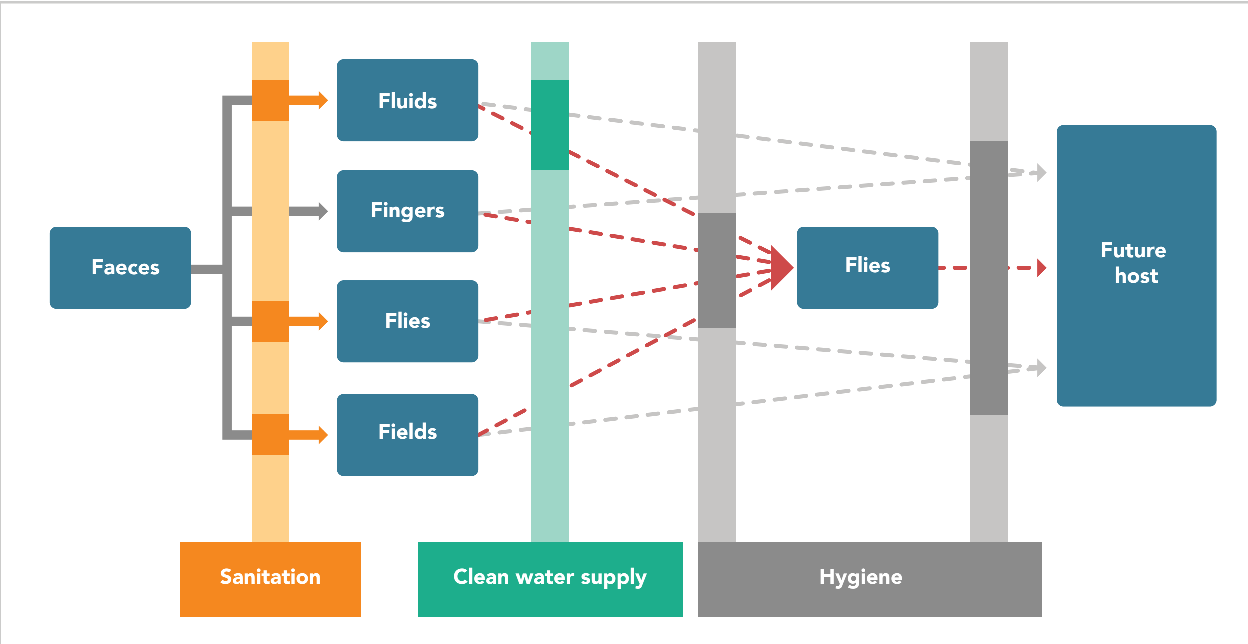

Exhibit 83. There are many pathways for disease transmission, which can be broken by interventions in the water, sanitation and hygiene sectors. "Fields" can refer to surfaces both inside and outside the home, and "fluids" includes drinking water and other contact with surface water, such as for bathing or recreation. (Source: adapted from Tilley et al. 2014b)

Young girls collect water in metal vessels.

The types of systems and technologies used to collect and treat faecal waste depend on how densely populated an area is, and on the resources available to households and local authorities to devote to sanitation practices (see Table 11).

Rural areas are typically less densely populated, thus distributed small-scale on-site faecal waste management techniques are appropriate. In more densely populated urban areas, a more appropriate solution is water-based transport of faecal waste through sewer networks to centralised sewage treatment facilities (although discharge of untreated sewage into rivers is more common in practice).

Peri-urban areas share some characteristics of both urban and rural areas, and the best sanitation management option for such areas will depend on the specific population size and density, distance to an urban centre, and various environmental factors such as soil type and groundwater table depth.

	Sanitation method	Human health risk			
		Initial hygenic separation	Secondary exposure risk	Surface water contamination	Ground water contamination
On-site decentralised	Open defecation	Very High	Very High	Very High	Medium
	Simple pit latrine (not emptied)	High	Medium	Low	Very High
	Improved pit latrine (safely emptied)	High	Low	Very Low	Very High
	Improved pit latrine (unsafely emptied)	High	High	High	Very High
	Pour flush + single pit (safely emptied)	Very Low	Very Low	Very Low	Very High
	Pour flush + single pit (unsafely emptied)	Very Low	High	High	Very High
	Pour flush + twin pit (safely emptied)	Very Low	Very Low	Very Low	Very High
	Pour flush + twin pit (unsafely emptied)	Very Low	Medium–High	Medium–High	Very High
	Pour flush + septic tank (safely emptied)	Very Low	Very Low	Very Low	High
	Pour flush + septic tank (unsafely emptied)	Very Low	High	High	High
	Pour flush + vermi-filter (safely emptied)	Very Low	Very Low	Very Low	Medium
	Pour flush + vermi-filter (unsafely emptied)	Very Low	Medium	Low	Medium
Off-site centralised	Sewer network to river	Very Low	High	Very High	Low
	Sewer network + primary treatment	Very Low	Medium	High	Low
	Sewer network + secondary treatment	Very Low	Low	Low	Very Low
	Sewer network + tertiary treatment	Very Low	Very Low	Very Low	Very Low

Legend: Very Low, Low, Medium, High, Very High

Table 11. A range of on-site and off-site sanitation technologies are available, each providing a different level of health risk reduction. Health risk is described here as a function of the initial hygienic separation of the faecal waste, and the opportunities for secondary exposure to the faecal pathogens, which include the risks of surface and groundwater contamination. The methods used for pit emptying and faecal residue management have a major impact on overall health risk. (Source: ITT analysis based on multiple sources)

In rural areas, decentralised on-site sanitation systems for individual households are most appropriate since they do not require a sewer connection, are relatively affordable, and can safely contain the faecal waste when managed properly. A wide range of on-site sanitation technologies have been developed, including pit latrines (single and twin pits), pour-flush pit toilets (with septic tanks, and single and twin leach pits), vermi-filtration toilets, dry composting toilets, and anaerobic baffled reactor toilets.

The cost and performance of various on-site sanitation systems are compared in Exhibit 84. Lifecycle costs include the initial capital cost, plus ongoing operations and maintenance costs, primarily for emptying of faecal sludge. In general, health risks are reduced as the cost of the on-site sanitation system increases.

An exception to that trend is vermicomposting toilets which provide high performance at low cost, largely due to enhanced decomposition of faecal matter by earthworms, leading to less waste build-up and less frequent emptying, thus lower maintenance costs. Toilets with leach pits are simple and fool proof and are appropriate for hesitant users who have recently switched from open defecation. More sophisticated on-site waste management technology, such as the vermi-filtration toilet, provide greater overall sanitation protection and are appropriate for experienced users. Thus, a phased approach may be needed with the long-term goal of universal sanitation coverage with highly effective local waste processing capabilities.

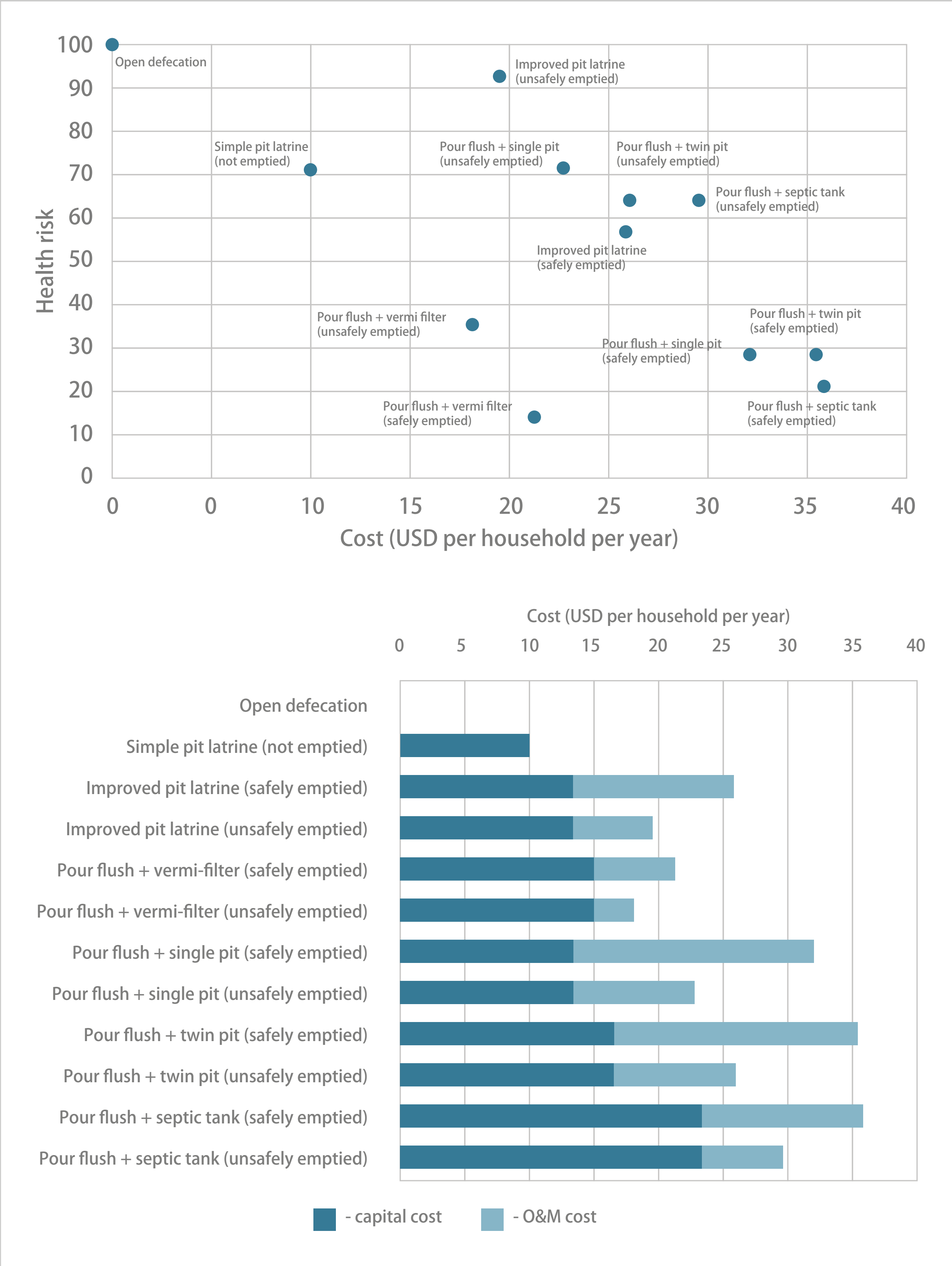

Exhibit 84. A range of on-site sanitation technologies are available, and more expensive technologies generally provide greater health risk reduction. The lifecycle cost of sanitation options includes both the capital cost and the operations and maintenance costs, which vary significantly between technologies (Source: ITT analysis of Indian context, based on multiple sources)

Decentralised on-site sanitation systems should be viewed as a long-term solution to rural sanitation, rather than an interim fix, and should be given a high priority in resource allocation. In order for on-site sanitation systems to be effective, mechanisms must be developed to regularly empty the sanitation facilities and transport the faecal sludge, as necessary, to appropriate sites for reuse or disposal. From toilet siting and construction, to sludge emptying and transport, to final treatment and disposal of waste, each step of the sanitation service chain is critical in achieving effective sewage management (Blackett et al. 2014).

Densely populated urban centres typically use centralised systems, which collect wastewater from many households and transport it out of the urban area, ideally to a large-scale facility for treatment. Such systems require large upfront costs and high operational and maintenance costs, as well as large investment of human capital.

Wastewater is collected and usually conveyed in sewer pipes to outside the city centre. There, it may either empty directly into a river without any treatment, which is most common in South Asia, or it may be treated followed by discharge to a river. Wastewater may be treated to primary, secondary, or tertiary levels, with progressively better water quality. It may also empty into a wetland (e.g. Kolkata), or the water may be treated and reused for various purposes (e.g. agriculture, aquaculture, municipal water) (WWAP 2018). Wastewater reuse is discussed in detail in Section 6.8.2.

Sewage treatment can consist of a combination of physical, chemical, and biological processes to remove solids, pathogens, and biochemical oxygen demand (BOD). Physical processes (primary treatment) include the use of gravity as well as physical barriers, such as filters and membranes, to separate out large solids. Membrane systems typically require high energy consumption and high levels of operation and maintenance.

Biological processes (secondary treatment) contain a variety of microorganisms that decompose the sewage; these processes can operate under either aerobic or anaerobic conditions. Aerobic conditions require more energy for aeration but produce sludge as a by-product, which can be applied to fields as a fertiliser or soil conditioner. Anaerobic processes require less energy and produce less stabilised sludge, but the methane produced as a by-product can be captured and used as an energy source (WWAP 2017). Combining aerobic and anaerobic processes, e.g. using UASB and ASP in a sequence (Table 12), in a single plant can help save energy costs and improve effluent quality (von Sperling et al. 2001).

Chemical processes (tertiary treatment) are often used for disinfection (e.g. ferric salts to remove BOD and solids) or to remove nutrients (e.g. iron-sulphate to remove phosphorus). Constructed wetlands are engineered to mimic the natural purifying abilities of wetlands and estuaries and can treat sewage to the secondary degree (WWAP 2018). All of these processes can be combined in sequence to obtain the cleanest effluent (UNEP 2016).

Centralised, large-scale sewage treatment systems are quite expensive, energy intensive, and typically require skilled personnel to operate and maintain the plants. Conventional wastewater treatment methods are a major resource sink. In the United States, for example, about 1.3% of all electricity is used for sewage treatment (Heidrich et al. 2011). This is a wasted opportunity, because raw sewage contains about six times more chemical energy than the amount of electrical energy required to treat it (Korth et al. 2017).

The chemical energy contained in wastewater can be exploited in several different ways. Methane harvesting from anaerobic digestion is a well-known energy saving and energy producing method. Its drawbacks are its requirements of high concentrations of organic matter, warm wastewater temperatures (i.e. >20 °C), and a high minimum flow rate.

Newer energy generation methods include microbial electrochemical technologies, such as microbial fuel cells and microbial electrolysis cells, the use of microalgae for biodiesel, and anaerobic membrane bioreactors, which can produce methane from low concentrations of sewage (Rao et al. 2017). Alternative methods include the combined use of micro- and macro-organisms, such as vermicomposting, in which the compost can later be retrieved to recover nutrients.

Table 12 summarises the characteristics of various off-site sewage management technologies and their suitability for use in different geographic and economic settings. Important selection criteria for treatment technology include the land area available, the economic resources available for capital and O&M, and the quality requirements for the reused water.

Prior to entertaining tertiary treatment at any location, it is advised that sewage treatment plants in South Asia are first deployed with the capacity to treat all wastewater in that area to the level of secondary treatment (BOD <20 mg/L, suspended solids <30 mg/L). Once there is high coverage of secondary treatment across the South Asian region, resources may be allocated to upgrade the plants to complete tertiary treatment (BOD <10 mg/L, suspended solids <15 mg/L, total faecal coliforms <2500 MPN/100 mL) (CPCB 2005).

Regardless of which sewage treatment system is used, the costs of not implementing and not investing adequate funds in sewage management are typically far greater than the costs of doing so, especially when the direct and indirect effects to public health, socioeconomic development, and environment impacts are considered (WWAP 2017).

Technology Type	Land Requirement	Capital Costs	O&M Costs	Energy Requirement	Effluent Quality	Advantages	Disadvantages
Activated Sludge Process (ASP)	0.15-0.25 hectares/MLD installed capacity	$41K-82K /MLD capacity	$6K-10K/year/ MLD installed capacity	180-225 kWh/ML treated	BOD: 10-20 mg/L Suspended solids: 20-50 mg/L	Low land requirement; resistant to organic and hydraulic shock loads; high reduction of BOD and pathogens; high nutrient removal possible; high quality effluent; biogas can be harvestedt	High energy consumption; high capital and operating costs; requires skilled personnel to operate and maintain; prone to complex chemical and microbiological problems
Trickling Filter (TF)	0.25-0.65 hectares/MLD installed capacity	Relatively lower than ASP	Slightly lower than ASP	180 kWh/ML treated	Comparable to ASP	Simple process; requires small land area; can be operated at a range of organic and hydraulic loading rates; efficient reduction of ammonia-nitrogen concentrations; low power requirements	Prone to clogging; regular operator attention necessary; potential for odour and vector problems; high capital costs; requires skilled personnel to operate and maintain; pre- or primary treatment required
Waste Stabilisation Pond (WSP)	0.8-2.3 hectares/MLD installed capacity	$31K-93K/MLD capacity	$1K-2K/year/ MLD installed capacity	Energy required for the operation of screen and grit chamber - negligible compared to ASP	BOD: 30-50 mg/L Suspended solids: 75-125 mg/L	Low O&M costs; low O&M capital; high BOD and pathogen removal; construction can take place by unskilled laborers; no electrical energy required	Requires large surface area; effluent contains nutrients and cannot be discharged into surface waters; prone to smelling, long processing time depending on climate
Upflow anaerobic sludge blanket (UASB)	0.2-0.3 hectares/MLD installed capacity	$52K-72K/MLD capacity	$2K-4K/year/ MLD installed capacity	10-15 KWh/ML sewage treated	BOD: 30-40 mg/L Suspended solids: 75-100 mg/L	Can absorb organic and hydraulic shock loading; low sludge production; biogas can be captured; little energy consumption; low land demand; can be constructed underground; effluent rich in nutrients	Sensitive to power cuts since constant electricity is required; operation and maintenance by skilled personnel; difficult to maintain proper hydraulic conditions (upflow and settling rates must be balanced); not adapted for cold climates
Rotating biological contactor (RBC)	0.008 hectares/MLD installed capacity			Very low compared to ASP	Comparable to ASP	High contact time and high effluent quality, stable process - resistant to shock hydraulic and organic loading; shorter process time; low land requirement; ease of installation and commissioning; simple to operate and maintain; low sludge production	Requires continuous electricity supply (but less than TF or ASP); high capital and O&M costs; must be protected against sunlight, wind, rain and freezing temperatures; odour may occur; requires skilled technical labour to operate and maintain; requires primary treatment (settling)

Technology Type	Land Requirement	Capital Costs	O&M Costs	Energy Requirement	Effluent Quality	Advantages	Disadvantages
Sequencing Batch Reactor (SBR)	0.1-0.15 hectares/MLD installed capacity	Higher than ASP	Higher than ASP	150-200 kWh/ML treated	BOD: <5 mg/mL suspended solids: <10 mg/mL	Equalisation, primary clarification, biological treatment, and secondary clarification can be achieved in a single reactor vessel; operating flexibility and control; minimal footprint	Requires higher level of sophistication of operate; higher level of maintenance; aeration device can clog
Fluidised Aerobic Bed (FAB)	0.06 hectares/MLD installed capacity	$62K-103K/MLD installed capacity	$10K-15K/year/ MLD installed capacity	99-170 kWh/ML sewage treated	BOD: <10 mg/mL suspended solids: <20 mg/mL	No sludge recycling and monitoring of mixed liquor suspended solids (MLSS); allows for continuous, automatically controlled operations	Expensive to construct and maintain; reactor walls may erode
Submerged Aerobic Fixed Film (SAFF) reactor	0.05 hectares/MLD installed capacity	$145K/MLD installed capacity	$24K/year/MLD installed capacity	390 kWh/ML treated	BOD: <10 mg/mL suspended solids: <20 mg/mL	More compact than conventional STPs	High energy use
Membrane Bioreactor (MBR)	0.035 hectares/MLD installed capacity	$62K-103K/MLD installed capacity	$12K-16K/year/ MLD installed capacity	180-220 kWh/ML treated	BOD: <5 mg/mL suspended solids: <10 mg/mL	Low footprint; high effluent quality; high loading rate capability	High O&M costs; high energy costs; membranes are complex and can foul
Duckweed Pond System (DPS)	2-6 hectares/MLD installed capacity	Similar to WSP	$4K/year/MLD installed capacity	Very low compared to ASP	BOD: <10 mg/mL suspended solids: <10 mg/mL	Easy to harvest; less sensitive to surrounding environmental conditions; high nitrogen removal; excess duckweed can be used for animal feed	Duckweed can die-off if not designed properly
Root Zone Treatment System (RZT)	0.1-0.2 hectares/MLD installed capacity	$21K-31K/MLD installed capacity	$1K/year/MLD installed capacity	Very low compared to ASP	BOD: <5 mg/mL suspended solids: <5 mg/mL Colourless	Low cost, high pathogen removal	Requires pre-treatment (settling)
Anaerobic Baffled Reactor + RZT	0.7-0.8 hectares/MLD installed capacity	$21K/MLD installed capacity	<$1K/year/MLD installed capacity	N/A	BOD: <5 mg/mL suspended solids: <10 mg/mL	No electrical energy required; resistant to organic and hydraulic shock loads; low O&M costs; high reduction of BOD; low sludge production; RZT provides high reduction of nutrients	Requires large land area

Table 12. There is a wide range of off-site sewage treatment technologies that may be used in cities and peri-urban areas. (Source: adapted from CSE 2011, with inputs from Nhapi et al. 2003 and Tilley et al. 2014a; costs are in US dollars; MLD = million litres per day; ML = million litres)

While numerous "hard" technologies are required to manage faecal waste, there is an equally important "soft" side to sanitation that involves devising and implementing effective policies and understanding how to influence technology adoption and behaviour adaptation. For example, the Government of India spent over USD 1 billion (INR 6475 crore) from 2014 to 2016 in an attempt to end rural open defecation by subsidising a toilet for each household under the Clean India Mission (Gopalakrishnan 2015).

Even though toilet coverage is increasing, adoption and usage remain low, and over 50% of India's rural population continues to defecate in the open (JMP 2017). Improved sanitation at the household level has little benefit to the growth and health of children if other households in the community do not also use improved sanitation facilities (Andres et al. 2014).

A variety of soft sanitation tools are available, including participatory planning tools, hygiene awareness and behaviour change, and sanitation promotion to create demand (Peal et al. 2010). Such soft tools have been a critical factor in improving sanitation conditions in Bangladesh in recent decades (World Bank 2016). However, Total Sanitation Campaigns (TSC) in Madya Pradesh state and other locales in India have been less successful, and other persistent concerted steps need to be taken to improve outcomes (Patil et al. 2014).

Water safety plans (WSP) are developed as a first step to assess and then continuously prioritise and manage risks to the water supply (WHO 2012). From a regulatory perspective, it is necessary to monitor water quality of nearby water bodies and to report discharges (WWAP 2017). In practice, water quality monitoring stations exist in South Asia and government agencies occasionally monitor, but the number of stations and frequency of monitoring is insufficient to ensure that pipes and plants are not leaking and that there are no untreated discharges. The Water Quality Index (WQI) developed by the National Sanitation Foundation is a standard tool to compare water quality across locations over time and to communicate water quality to various stakeholders (UNEP 2016).

6.7.2 Industrial effluent management

As noted in Section 3.6, a wide variety of industries in South Asia produce a diverse mix of waste products, which have commonly been discharged untreated into the nearest water body. Regulations that may have prohibited such dumping were absent, not enforced, or corrupted. More recently, however, increased societal concerns for a clean and healthy living environment have raised pressure in South Asia (and globally) for improved industrial waste management practices.

During recent decades, regulation of water quality and environmental protection has become stronger in Europe, North America and parts of Asia. This has stimulated a range of technological innovations to reduce or eliminate discharge of water pollutants, which are increasingly adopted by industries (WWAP 2017). "End-of-pipe" solutions are available to manage existing effluent production, but more advanced solutions involve altering industrial processes to eliminate the source of pollutants. Broad implementation of global best practices within South Asia would significantly reduce industrial effluent discharge and improve water quality.

Existing chemical waste sites may be a long-term source of surface and ground water contamination, unless the sites are remediated. A range of remediation techniques can be used, depending on the types of contaminants, their location in the ground or water, and the resources available for treatment (USEPA 2002). Bioremediation may be a cost-effective way to treat both organic and inorganic chemical contaminants on-site, and several microbial and fungal species have been shown effective at removing difficult contaminants such as heavy metals and endocrine disrupters (Pezzella et al. 2017).

6.7.3 Agricultural run-off management

The amount of fertilisers and pesticides used in South Asia has increased strongly since the 1960s (see Exhibit 85). While contributing greatly to the food security of the region, it has also caused significant environmental impact due to run-off. In particular, fertiliser run-off leads to nutrient enrichment of surface water bodies, causing eutrophication. Roughly 20% of nitrogen (N) fertiliser and 5% of phosphorus (P) fertiliser runs off of farm land and contaminates surface water (NRC 2000; MEA 2005). The amount of P entering Indian surface water from fertiliser run-off is roughly equal to the amount of P from human faeces and urine discharged from sewers, while the amount of N from Indian fertiliser run-off is about 6 times more N than from sewers (see Exhibit 86). Excess of P typically causes more eutrophication than N, as P is the limiting nutrient in aquatic ecosystems more often than N.

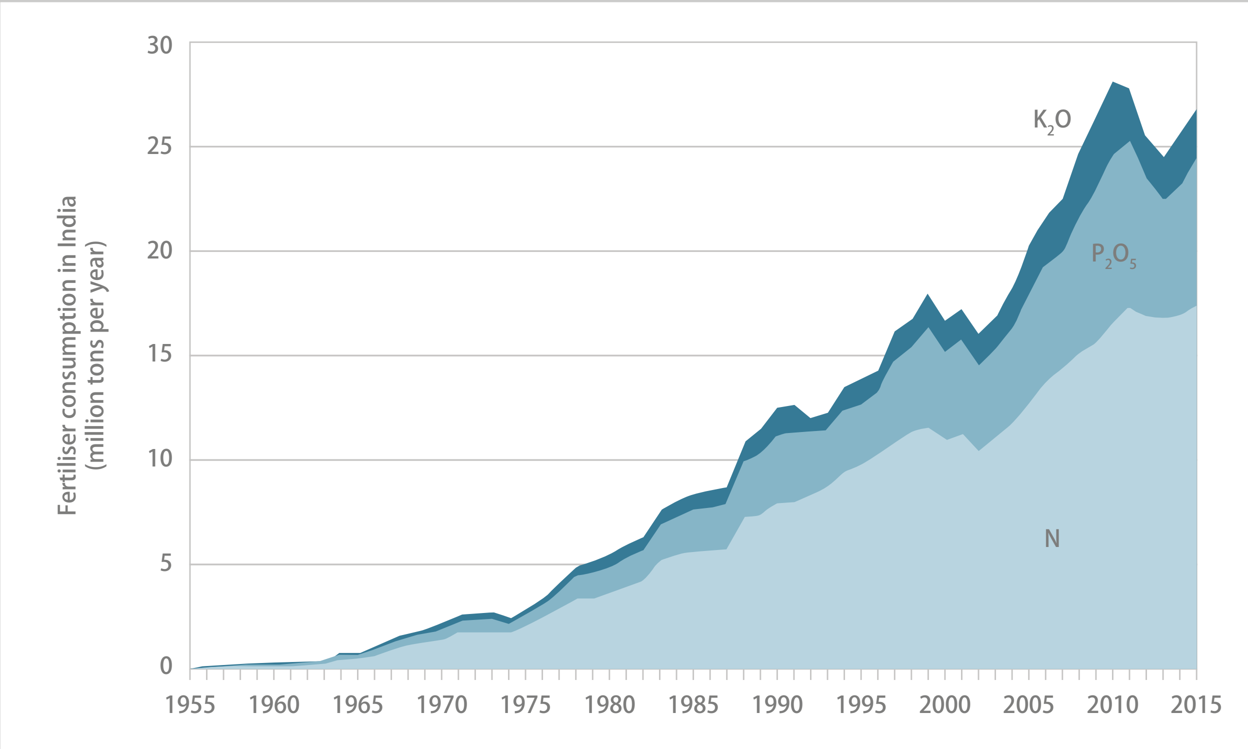

Exhibit 85. Fertiliser consumption in India has increased substantially in recent decades, as agriculture has become more intensive. (Source: data on all-India consumption of N, P_2O_5 and K_2O from Fertiliser Association of India 2016)

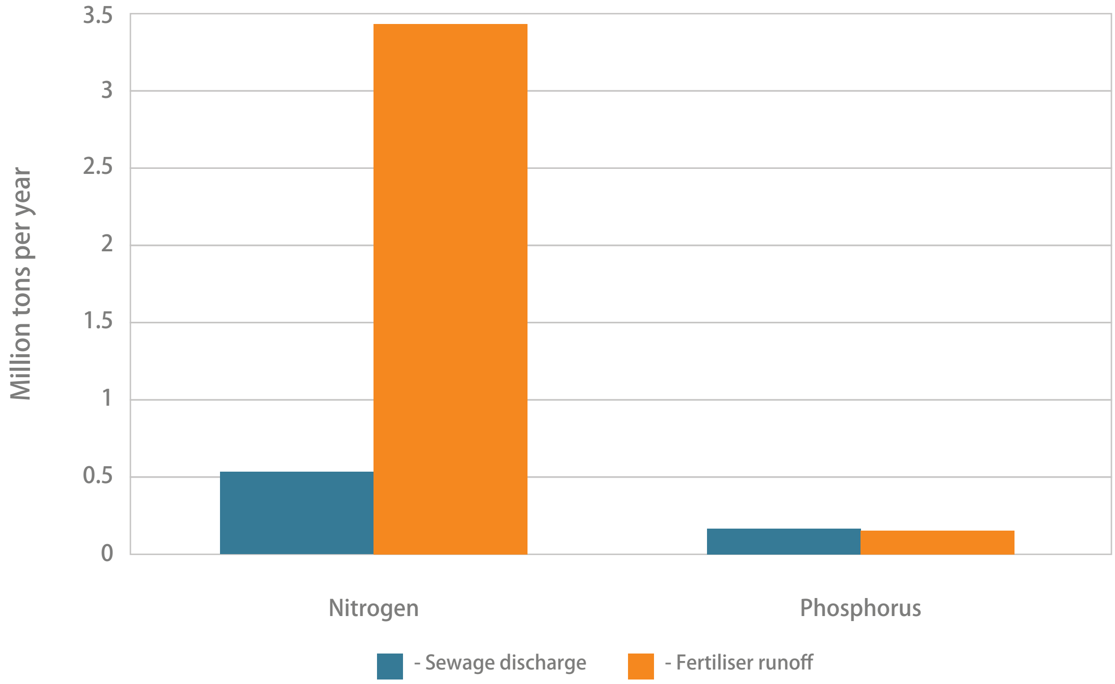

Exhibit 86. Release of excess nutrients such as nitrogen (N) or phosphorus (P) can cause severe water quality problems due to eutrophication. Fertiliser run-off from Indian farm land releases about six times more N, and about equal amounts of P, compared to human waste discharged from Indian sewers. (Source: ITT analysis based on: For fertiliser run-off, all-India fertiliser consumption from Fertiliser Association of India 2016, percent run-off of N (20%) and P (5%) from NRC 2000 and MEA 2005; For sewage discharge, all-India population from UN 2017, urban percentage from UN 2018, urban sewer connection rate from JMP 2017, average per capita faeces and urine discharge from Rose et al. 2015, percent nutrient content of faeces and urine from Rose et al. 2015)

Implementation of global best practices would significantly reduce the percentage of applied fertiliser that runs off of farm fields into water bodies. Appropriate nutrient management, by applying fertilisers in the proper amount at the right time and with the right method, can significantly reduce the potential for run-off (FAO 1996). Other good practices include planting cover crops and buffer strips, employing conservation tillage practices, and managing livestock waste (WWAP 2017).

Climate change may, however, impact efforts to improve farm nutrient management, as nitrogen run-off is projected to increase due to changes in precipitation patterns (Sinha et al. 2017). Management of paddy straw and other crop residue is a strong lever for improvement in some areas. In Punjab and Haryana, for example, farmers typically burn crop residue, losing important potential nutrients as well as causing significant air pollution (Lohan et al. 2018). Proper management of crop residues can improve soil health and reduce fertilizer consumption and run-off, particularly nitrogen.

6.7.4 Manage saline groundwater intrusion

Fresh groundwater aquifers are often surrounded by saltwater on one or more sides or underneath. Since freshwater is less dense than saline water, it tends to flow on top of the surrounding or underlying saline ground water. Under natural conditions, the boundary between freshwater and saltwater maintains a stable equilibrium. Under some circumstances, the saltwater can move (or intrude) into the freshwater aquifer, making the water unpotable. When freshwater is pumped from an aquifer that is near saline groundwater, the boundary between saltwater and freshwater moves in response to the pumping. If this continues, unusable saline water will be pumped up from the well.

Freshwater aquifers are naturally recharged by rainwater, and the recharge rate can be manipulated by managed aquifer recharge (MAR, see Section 6.4.3). Thus, there is dynamic interplay between freshwater withdrawals, freshwater recharge, and surrounding saline aquifers. Rising sea levels due to climate change are slowly increasing the gradient of saline water, although coastal aquifers are more vulnerable to groundwater over-extraction than to predicted sea-level rise (Ferguson & Gleeson 2012).

Techniques are under development to manage saline groundwater intrusion. Actions, such as controlling the rate and depth of groundwater extractions and augmenting freshwater recharge by MAR, can reduce or eliminate undesired saline intrusion. Skimming wells can also be used to sustainably exploit fresh groundwater lenses that overlie native saline groundwater (Saeed & Ashraf 2005). The freshwater lenses are renewed through deep percolation of rainwater and irrigation water. Skimming wells are designed and operated to minimize the mixing between overlying freshwater and underlying saline water.

Successful management of saline groundwater intrusion requires a deep understanding of aquifer dynamics and how they may be manipulated. The tools of groundwater mapping, described in Section 6.6.1, can provide the required knowledge of the hydrogeological landscape.

6.8 Reuse and recycle water

Wastewater reuse is becoming more common in water-scarce regions, where wastewater is increasingly seen as a resource and not as waste (WWAP 2017). Potential levers for enhancing water security in South Asia include the direct reuse of household grey water and the treatment and reuse of wastewater from industries, municipal sewers and agricultural run-off. Reusing wastewater brings two important benefits: less pollution entering water bodies, and less need for freshwater withdrawals. However, in the areas where it is currently practiced, wastewater reuse is typically considered as a temporary solution for acute needs, instead of implemented as a long-term solution to improve water security.

6.8.1 Grey water reuse

Grey water is the term used to describe household wastewater that does not have significant faecal contamination, i.e. from sinks, showers, baths, washing machines, etc. Grey water can be directly reused for various applications that do not require potable water. For example, a household can use wastewater from their bathroom sink to flush their toilet. At a slightly larger scale, apartment buildings can use grey water to irrigate their landscaping.

Grey water has significantly fewer pathogens than sewage water and is typically safe to directly reuse for certain local, immediate small-scale applications. Larger-scale applications of grey water reuse are less suitable for two reasons. First, the quality of grey water can deteriorate rapidly during storage, because it is often warm and contains some nutrients and organic matter which allows microorganisms to multiply. Second, as grey water is aggregated from more disparate sources, it becomes more difficult to control and maintain the quality, resulting in grey water with unacceptable levels of chemical or faecal contamination. Large-scale reuse of wastewater therefore requires some level of treatment and is considered in Section 6.8.2.

Utilising grey water typically requires separate piping systems for potable water and grey water. It is thus more economical to build in the systems during construction, rather than to retrofit existing buildings. On a smaller scale, there is potential for well-designed consumer products that facilitate the reuse of drain water from bathroom sinks to flush toilets without the need for expensive retrofitting (see Exhibit 87). ITT estimates that if 80% of Indian urban households used grey water to flush their toilets, it would result in a total water withdrawal reduction of about 2.4 km^3 per year.

Exhibit 87. Example of direct grey water use: a sink in Japan that reuses water for toilet flushing. (Source: see Section 10, Photography References)

6.8.2 Large scale water treatment and reuse

The quantities of wastewater generated in South Asia are enormous, thus reusing this water for other purposes is a major lever for enhancing water security. If 80% of the wastewater collected by urban sewage networks in India were reused, an additional water resource of 18 km^3 per year would be obtained. Nevertheless, the large-scale treatment and reuse of water faces several challenges, depending on the intended use of the recycled wastewater and the scale of the treatment facility (van Rooijen et al. 2005).

Major reuse applications include agriculture (food and non-food crops), industry, and groundwater recharge, for which increasing effluent quality is required, respectively. For agricultural purposes, nutrient removal (or partial nitrogen removal) can be left out of the treatment process, whereas reuse in industrial applications or groundwater recharge requires nutrient and solids removal. Groundwater recharge applications may also require removal of micro-pollutants as well as organic carbon.

For each application, treatment typically consists of an activated sludge step, a filtration step, and a decontamination step. In terms of costs, the higher the quality of treated effluent, the higher the total capital and operational costs are. Generally, larger treatment plants have an increased efficiency, which lowers the lifecycle costs and environmental impacts per m^3 of treated water (Lazic et al. 2017).

There are many methods to reuse wastewater for other beneficial purposes. Engineered wetlands, for example, provide a natural way to both treat wastewater and allow it to percolate back into the ground to recharge water tables. Kolkata fisherman have been reusing wastewater from the city to feed their aquaculture ponds for decades.

Some sewage treatment technologies result in sludge, which can be dried in the sun and then applied on fields or buried, which recycles nutrients and conditions the soil. Furthermore, biogas and heat energy can be recovered from a range of treatment processes. Several countries have begun growing microalgae on sewage to produce biofuels, bio-plastics, bio-chemicals, and even nutrition supplements for humans and animals (WWAP 2017).

After some level of treatment, all components of sewage could be harvested and reused, including the elements in urine, faeces, and water. The most common reuse of wastewater is for agricultural irrigation, though it is necessary to treat the sewage to a hygienically-safe level before application, such as exposing to sunlight for long periods. Some farmers in Pakistan apply untreated wastewater on their fields, where freshwater is scarce. However, many suffer from hookworm infections and their fields are overloaded by nutrients, which underscores the need for pre-treatment before application (Khalil & Kakar 2011).

6.9 Inter-basin water transference

Transferring water from river basins with abundant water resources to other basins that are water scarce, is an often-discussed large-scale intervention to enhance water security. Inter-basin water transference is not a new concept and has been implemented in South Asia since at least the 17th century. Examples of existing inter-basin transfers in South Asia include:

- the Kurnool Cudappah Canal, transferring water from the Krishna River basin to the Penna basin since 1870

- the Periyar Project from the Periyar River in Kerala to the Vaigai basin in Tamil Nadu, commissioned in 1895

- the Triple Canal Project in Pakistan, constructed during 1907-1915, linking the Jhelum, Chenab and Ravi rivers, transferring Jhelum and Chenab water to the Ravi river

- the Indira Gandhi Canal, built in the 1960s, linking the Ravi River, the Beas River and the Sutlej River to irrigate the Thar Desert

- the Parambikulam Aliyar project, transferring water from the Chalakudy River basin to the Bharathappuzha and Kaveri basins

- the Telugu Ganga project, completed in 2004, bringing Krishna River water to the city of Chennai

- the Pattiseema scheme, beginning operation in 2015, linking the Krishna and Godavari rivers.

The proposed Indian River Inter-link project continues this tradition but on a much larger scale than previous efforts. The project aims to connect northern Indian rivers with southern Indian rivers through a network of canals, dams and pumping stations. Given the long time frame for completion, the significant opportunity costs of the substantial resources required, and the social cost to displaced households, there is significant uncertainty about the net benefits of the project.

Long-distance physical transfer of water requires capital-intensive fixed infrastructure with little flexibility to adapt to future changes (e.g. climate change). In contrast, a less expensive and more flexible approach may be found in distributed investments in end-use efficiency measures such as irrigation and industrial modernisation, and system integration measures such as wastewater treatment and reuse.

Furthermore, permanently diverting water away from regions that currently have "excess" water denies those regions the opportunity to develop local productive uses for the water. Although some additional inter-basin transfer projects are likely to prove worthwhile individually, the proposed Indian River Inter-link project as a whole is unlikely to contribute significantly to Indian water security.

Other forms of inter-basin water transfer include proposals for towing of icebergs from polar regions to provide fresh water to coastal areas. Eventual small-scale implementation of this idea in some wealthier and dryer regions of the world will not be surprising, though iceberg transfer is not expected to play a significant role in South Asia's water future.

Large-scale, long-distance humanitarian water transfer is an increasing phenomenon. In 2016, emergency water transfers were made by train to Latur, Maharashtra, to supplement local water sources depleted by drought and overuse. Extremely expensive per litre of delivered water, the need for such interventions should be avoided if at all possible by appropriate management of local water supply and demand.

6.10 Drainage management

6.10.1 Sub-surface drainage

Sub-surface drainage plays an important role in managing waterlogging and salinization in irrigated agriculture. Need for such management is determined by the amount and timing of irrigation and rain water, the salt content of irrigation water, and the local climatic and soil conditions. Where natural drainage is inadequate, active measures must be taken to ensure drainage of irrigated crop land.

Great advances in managing salinization and waterlogging have been made in South Asia during the past 50 years. Pakistan faced a crisis in the 1950s and 60s, with a rapidly increasing percentage of farmland affected by waterlogging and salinity, as gradually rising water tables finally approached the land surface (Bhutta & Smedema 2007).

Pakistan implemented a series of large-scale drainage projects such as Salinity Control and Reclamation Project (SCARP), Left Bank Outfall Drain (LBOD), and several Right Bank Outfall Drain (RBOD) projects (Chaudhry 2010). Most of the large public SCARP borewells have been abandoned and farmers have been provided support to install shallow borewells (Zaman and Ahmad 2009). These drainage efforts have partially alleviated Pakistan's drainage problems. In recent decades the waterlogged area has increased in Sindh province, whereas Punjab province has experienced considerable reduction in the waterlogged area mainly due to the extraction of large amount of groundwater from private borewells.

Best practices in terms of agricultural salinization and waterlogging have been largely developed, and require widespread appropriate farm-level management combined with basin-level coordination (Ayars and Evans 2015). For example, integrated and coordinated development of surface and ground water, commonly known as conjunctive use, is now widely recognised as a suitable strategy for irrigation development in alluvial regions.

Conjunctive use increases the irrigation potential by including both surface and groundwater, and also partially mitigates the problem of waterlogging by increasing groundwater extraction (India Planning Commission 2009). Management of waterlogging and salinization must be dynamic, accounting for changes in water quality and quantity. For example, weather variability affects waterlogging. In the 1990s waterlogging in the IBIS area of Pakistan was high, while droughts in the early 2000s resulted in lowering of the water table and reduction of the waterlogged area (FAO 2012).

Sub-surface drainage is often given low priority in agricultural development decisions, and seldom receives the attention and resources it deserves (Ritzema 2016). While other agricultural interventions (such as irrigation, seeds, fertiliser) give positive short-term returns, drainage is typically necessary to prevent long-term negative effects. In areas already affected by waterlogging, however, implementation of drainage practices can have significant positive effects on yield.

Long-term agricultural sustainability in South Asia will require active basin-level management to monitor salt build-up and maintain and expand drainage infrastructure. This will require strong long-term institutional and financial commitments.

Broad engagement of farmers will also be necessary, to implement appropriate on-farm water management practices based on local conditions. There is large scope for innovative information technologies to assist in basin-level management, by aggregating and analysing distributed data on environmental characteristics such as groundwater salinity and water table depth, and by conveying coordinated best-practice water-management recommendations to individual farmers that are customised to their local conditions.

6.10.2 Surface drainage

Surface drainage is the removal of excess water from the surface of the land to a natural water stream or an artificial drainage system. High surface run-off can cause flooding, erosion and decreased water quality. Surface drainage is normally accomplished by shallow ditches, also called open drains. The shallow ditches discharge into larger and deeper collector drains. In order to facilitate the flow of excess water toward the drains, the land must be sloped. The effectiveness of drainage systems is dependent on topography, rainfall amount and timing, and soil type. In cases of heavy rainfall, water can accumulate faster than it can drain away. Flooding can cause major damage to livelihoods and economic activity. The risk of flooding is higher among coastal and downstream areas (WRIS 2015) (see Exhibit 88).

Exhibit 88. Some areas of India are prone to flooding, due to local climate and topology.
(Source: https://commons.wikimedia.org/wiki/File:India_flood_zone_map.svg)

There are at least three approaches to reducing flood risk. One approach to mitigating the risk of flooding involves large-scale hard engineering of river courses. This can take the form of dams to store large quantities of water to prevent downstream flooding. It can also take the form of river engineering, by widening, deepening or straightening river channels to allow greater water flows.

Another approach involves numerous distributed measures for storing rainwater and increasing its infiltration into ground. These seek to reduce peak flows during rainy periods and attenuate the power of floods. Specific techniques include micro basins, gully plugs, field trenches, bunds, retention ponds/tanks, constructed wetlands, green roofs, infiltration tanks, soak pits, grass filters and swales, pervious pavements, and afforestation along river banks.

A third category of approaches involves policy and management effort (Sörensen et al. 2016). One example is managed flooding (also called ecological flooding) in which a river is allowed to flood naturally, in places, to avoid flooding in other places such as settlements. A further important example is effective planning, to control urban development on or near natural floodplains, to reduce the exposure to flooding. Resistance to development restrictions can be expected, especially where there is a high population density and shortage of housing.

While traditional efforts have typically aimed at flood "control" based largely on infrastructure, modern efforts generally aim for flood "management" using a process-based understanding of floods while favouring non-structural approaches to reducing flood risk (Raymahashay & Sinha 2012). These may include improved planning of human settlements to avoid high-risk floodplains, maintaining natural elements in river systems to increase hydrological resilience, and adopting flood insurance programs with realistic pricing of current and future risks.

6.11 Improve non-water agricultural factors

While Section 6.1.1 on irrigation water use efficiency improvements focused on methods to reduce water inputs to agriculture, here we consider non-water agricultural improvements that increase crop production without directly affecting water use. This indirectly enhances water security by increasing overall agricultural production, thus reducing the need for additional irrigation water to satisfy the growing demand for food.

6.11.1 Irrigated farms

Water supply is often the most difficult of farm inputs to supply, compared to e.g. fertiliser, seeds, pesticides and labour. Irrigation water requires relatively elaborate infrastructure, and is needed throughout the growing season. In contrast, most other agricultural inputs are more market-based, and needed only once or several times per season. If a farm is irrigated, the most difficult of agricultural inputs has thus been accomplished, and low yield is the result of (presumably solvable) management or market failures. Farm-level management may be improved by stronger agricultural extension services to inform about and advocate higher yielding, water conserving agricultural crops and techniques. Foresighted policy instruments including appropriate subsidies and taxes on inputs such as seeds, fertilisers and water can stimulate more rational consumption patterns within the agricultural sector.

An example of high potential non-water agricultural improvements is wheat production in India, which shows strong state-wise yield variability despite high irrigation coverage (see Exhibit 89). There is a 3X difference in yield between the highest and lowest performing states. Some of the variation may be explained by the quality of irrigation (unlimited and on-demand vs. limited and variable) but there is obviously great scope for increasing agricultural yields in low-achieving irrigated regions, via appropriate agricultural extension activities and other interventions. Many farmers could raise water productivity by adopting proven agronomic practices such as soil fertility maintenance and pest management (Molden & Oweis 2007). The highest gains in water productivity are likely in areas where yields are still low, warranting a development focus on regions with lower agricultural performance.

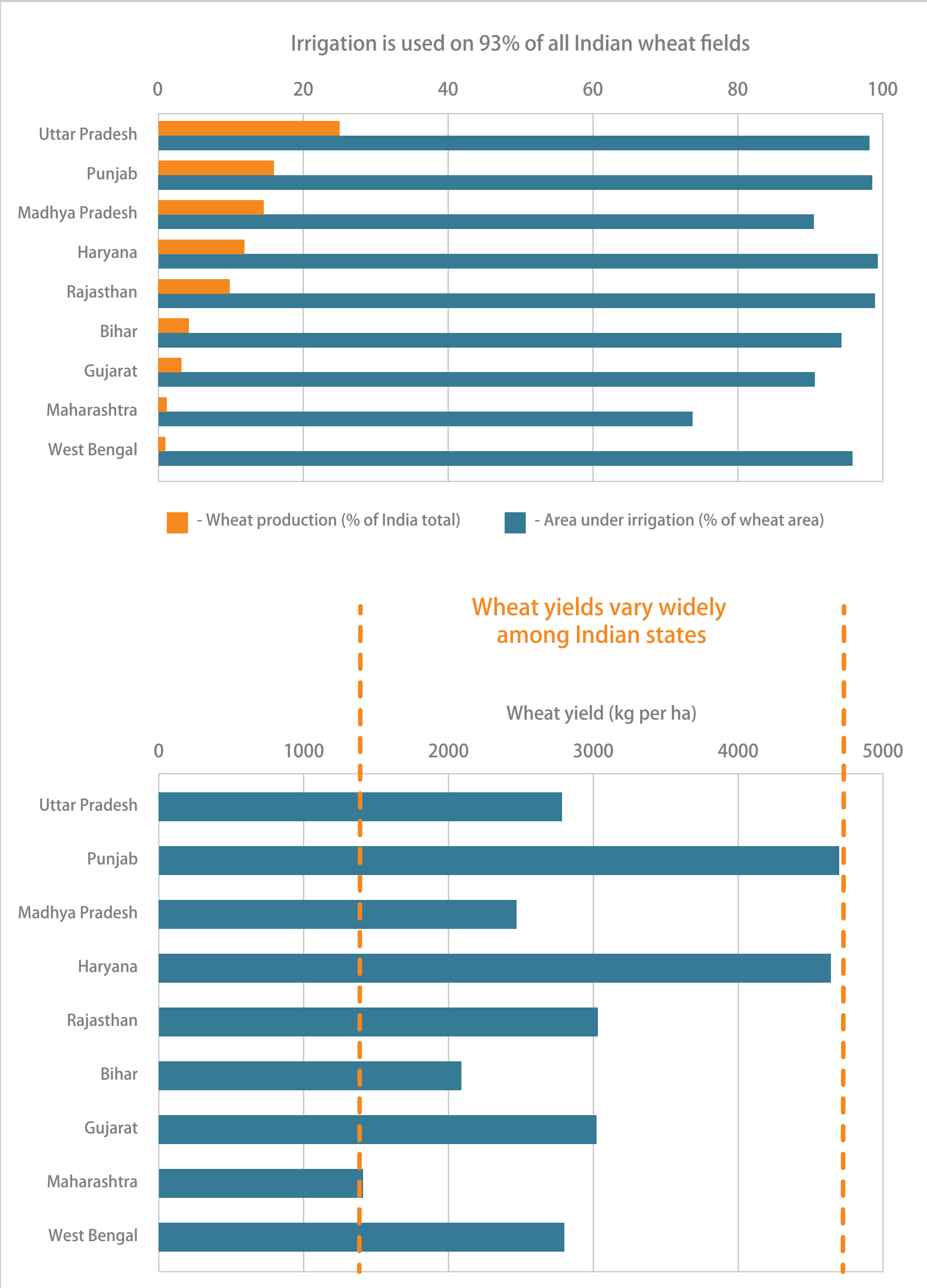

Exhibit 89. Despite widespread use of irrigation water for wheat cultivation in India (top), wheat yields per hectare vary considerably between states (bottom). (Source: data from India Ministry of Agriculture 2015; wheat production data is 2014-15, irrigation area data is 2012-13, yield data is average of 2013-14 and 2014-15)

6.11.2 Rainfed farms

An important part of South Asian agriculture does not use irrigation, and instead depends on rainfall for its water needs (see Exhibit 90). In India, 85% of the farmland under course cereals is rainfed, as is 82% of area under pulses, 72% of area under oilseeds, and 42% of area under rice (India Ministry of Agriculture 2015). Furthermore, two out of three livestock animals in India are supported by rainfed ecosystems. In Pakistan, rainfed farms produce 90% of groundnuts, 85% of pulses, 69% of sorghum, 53% of barley, and 80% of livestock (Baig et al. 2013). By making better use of the "green water" that falls on these dryland farms, total agricultural production may be increased without the need for problematic sourcing of additional water.

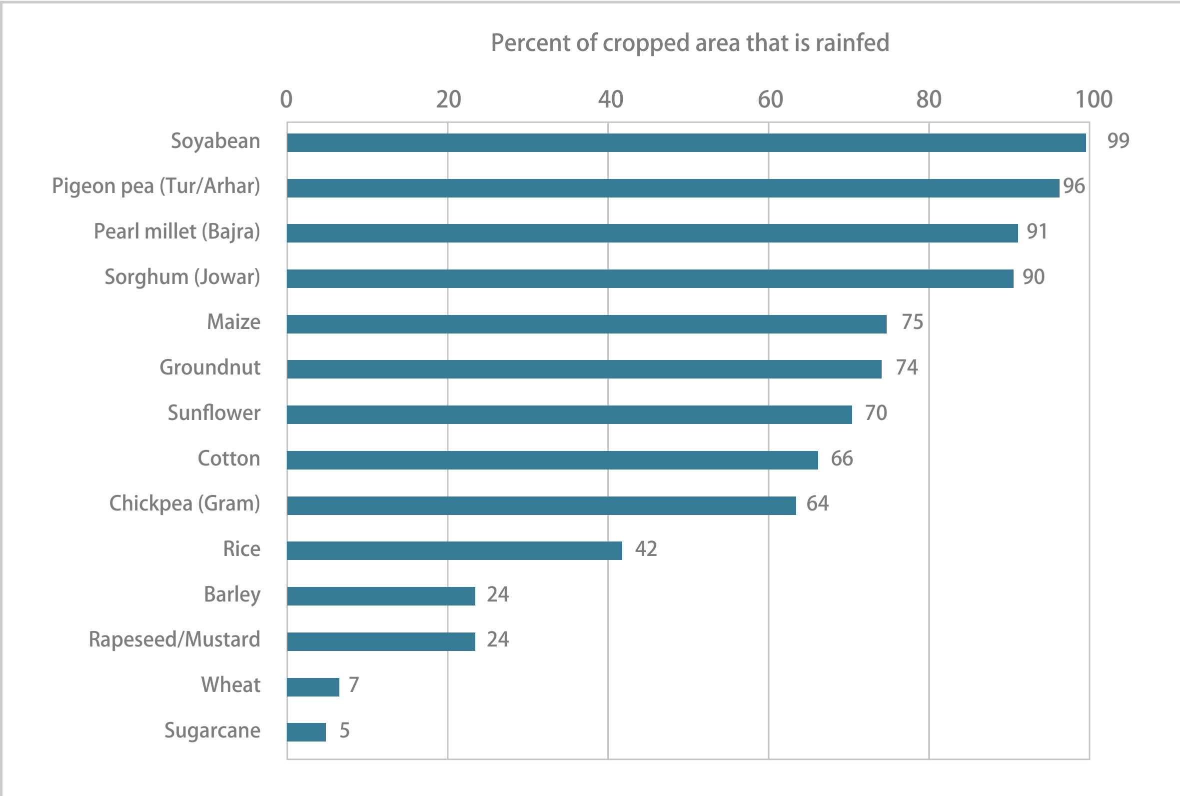

Exhibit 90. Many crops grown in South Asia are rainfed and do not use irrigation. There is a large opportunity to increase overall agricultural production by increasing yield and water-use efficiency of these crops. (Source: year 2012-13 all-India data from India Ministry of Agriculture 2015)

The potential production from rain-fed farms depends on many factors, including climatic factors such as precipitation, temperature and humidity, and geologic factors including topography and soil water storage capacity (Droogers et al. 2001) (see Exhibit 91). Within India, areas may be classified as rainfed for two distinct reasons (Kumar et al. 2018).

First, the area may receive adequate precipitation during the growing season, which meets the evapotranspiration rates of crops, so that they do not require irrigation. Second, the area may have very little natural water in the form of soil moisture or run-off, due to low rainfall and high aridity, thus only low-water and short-duration crops are grown in the rainy season. Yield improvements in the first areas can result from better general agronomic practices such as soil fertility and pest management, while the second areas can also benefit from on-farm water conservation measures.

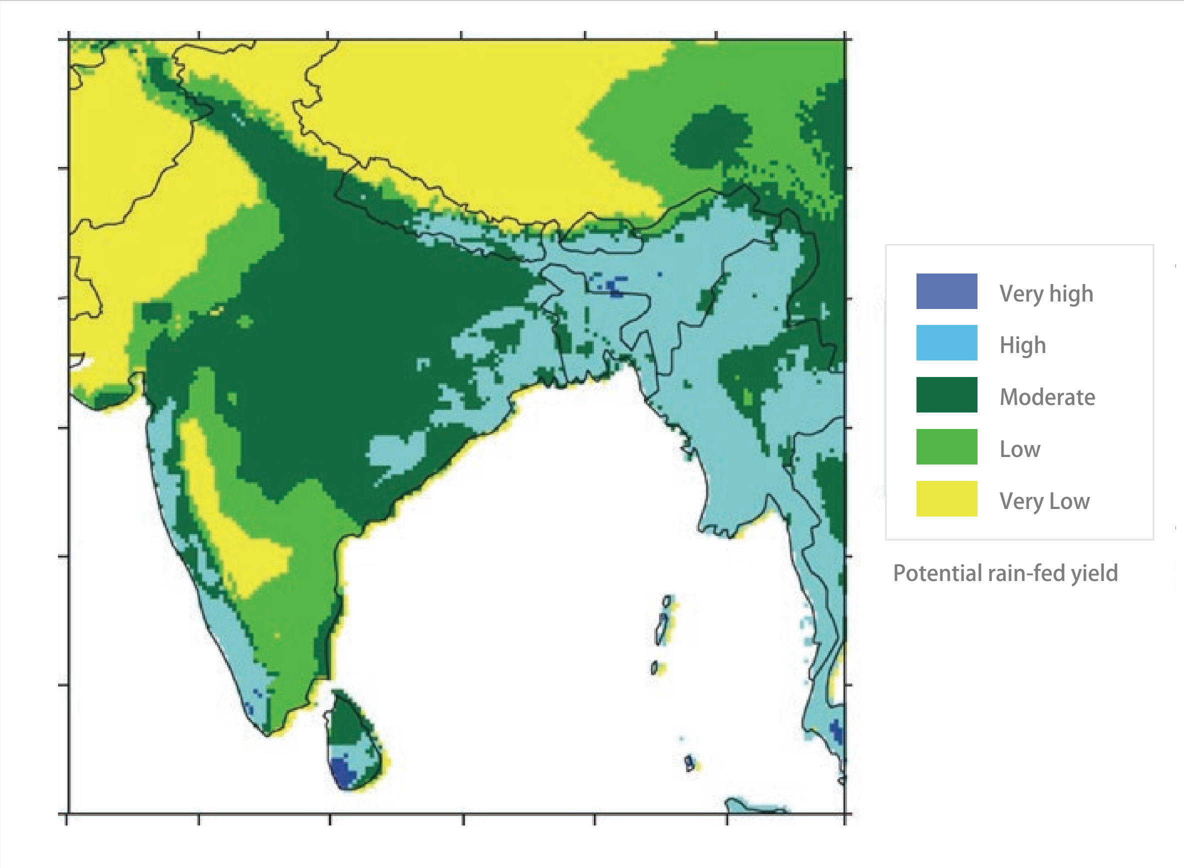

Exhibit 91. The potential for rain-fed agriculture varies widely in South Asia. It is low in western regions including Pakistan, high in eastern regions including Bangladesh, and quite varied in peninsular India. (Source: adapted from Droogers et al. 2001)

Knowledge already exists that, if put into practice, could double the yields from rainfed agriculture in some areas (Rockström et al. 2007). Where appropriate, adopting best-practice on-farm management provides an immediate and effective way to increase crop water productivity (FAO 2011) (see Exhibit 92).

There are three broad categories of actions to increase productivity of rainfed farms. First, in situ rainwater harvesting techniques seek to maximise the share of rainfall that infiltrates into farm soil, while minimising the share that runs off the farm fields. This is accomplished with bunds, ridges, furrows, terracing, or contour cultivation that detains rainwater that falls on the fields and allows it to percolate into the soil.

Second, integrated soil, crop and water management techniques reduce the amount of non-productive evaporation, while maximising the amount of water used for productive transpiration during photosynthesis. Reduced evaporation can be accomplished with mulching, optimal timing of planting, zero tillage technology, surface seeding technology, intercropping and windbreaks. Increased transpiration is achieved by nutrient management, integrated pest management, improved crop varieties, optimum crop geometry and rotation, and organic matter management.

Third, external water harvesting techniques seek to direct, concentrate and store run-off water from farm fields and adjacent lands, to be used as supplemental irrigation to mitigate dry spells during critical growth periods to avoid crop failure (Sharma et al. 2010). This is accomplished through surface microdams, farm ponds, percolation dams and tanks, and other groundwater recharge structures. The collected water can be stored in surface structures or in underground aquifers (see also Section 6.4.3). These three categories of actions will typically be implemented in order, thus ensuring efficient use of on-farm water resources prior to sourcing external inputs (e.g. fertilisers and seeds) and supplemental irrigation water.

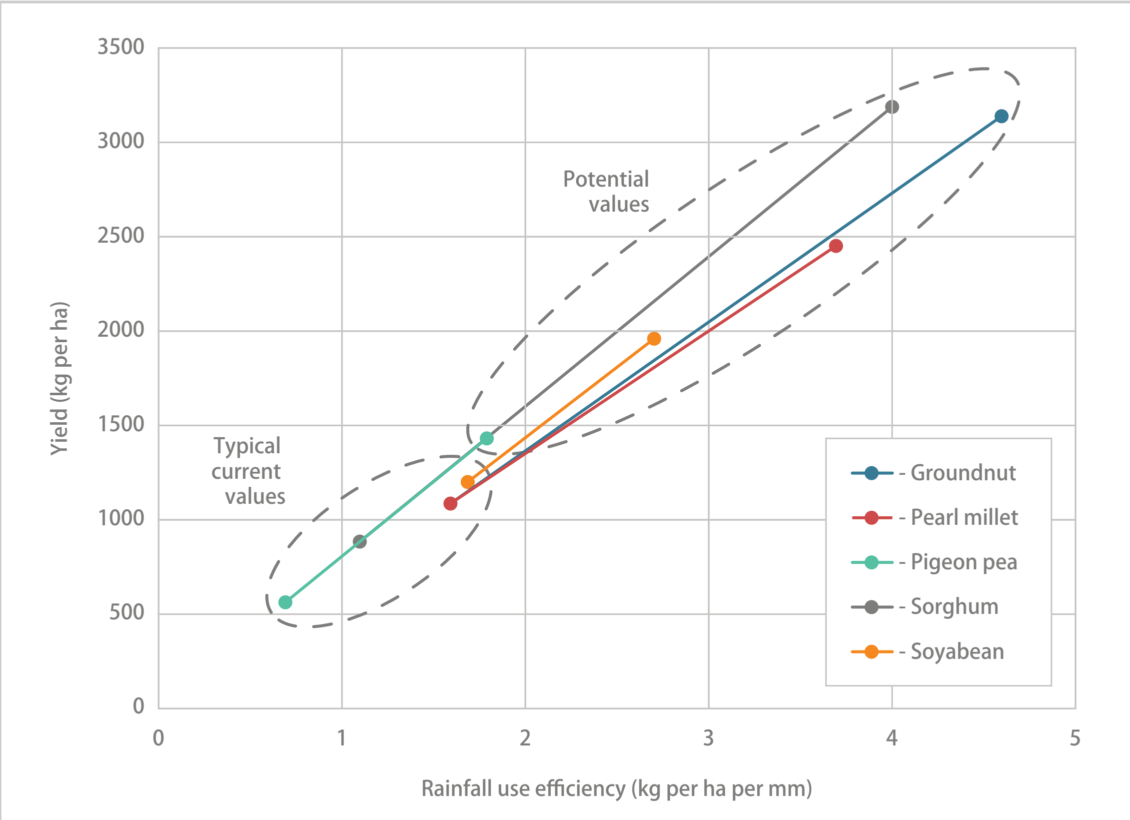

Exhibit 92. There are large gaps between current typical values and potential values of yield and rainwater use efficiency for rainfed crops in semi-arid zones of India. Technologies and practices are available to achieve the higher potential values of yield and rainwater use efficiency. (Source: data from Singh et al. 2011)

Rainfed farmers are typically (and understandably) reluctant to invest in fertilisers, improved seeds, and other components of modern agriculture, due to the inherent risk of crop failure when water supply cannot be guaranteed. Implementation of improved rainfed farming techniques thus initiates a virtuous circle, by reducing the risk of total crop failure, and economically incentivising and enabling further improvements. Important steps include expanded agricultural extension services to disseminate best practices to farmers, supported by relevant applied research conducted at experimental stations and on farms.

7. SUMMARY OBSERVATIONS

The water security challenges facing South Asia are complex and include issues of water quantity and water quality. No single intervention can definitively solve water security problems in the region, but numerous actions can be taken on many fronts to significantly enhance water security. Overall, the story of water security in South Asia includes both "bad news" and "good news." The bad news is, South Asia faces serious constraints to accessing adequate amounts of high-quality water to meet growing demands. The good news is, many current patterns of water use are quite inefficient so there are major opportunities for low-cost, high-impact improvements.

Important findings from this study include:

- Regions in closed river basins and/or with hard rock hydrogeology, such as Pakistan and much of peninsular India, face hard limits to absolute water supply rates. Continued economic and demographic growth will require water-efficient technologies, methods and attitudes.

- Poor surface water quality is largely due to inadequate management of human faecal waste. This imposes an immediate need to ensure purification of sewage-contaminated water prior to consumption, and a longer-term need to expand effective sanitation coverage to eliminate sources of contamination.

- Supplying water to growing cities will increasingly conflict with agricultural water needs, especially in closed basins and hard rock regions. Although total water use in urban areas is less than agricultural water use, each litre of urban water is more "valuable" than a litre of irrigation water, because of both essential household needs and high industrial economic returns.

- Water reuse and recycling is an important lever in regions of physical supply constraints. The quantities of wastewater generated in South Asia are huge, thus reusing this water for other purposes is a major option for enhancing water security. Coupled with wastewater treatment facilities, usable water supply can be increased while pollution discharge is avoided.

- Seawater desalination is a mature technology with little opportunity for efficiency improvements. Costs will continue to decline modestly as a function of scale and system integration. Brackish water desalination offers more significant opportunities for improving efficiency and cost.

- Contamination of water by environmental toxins is a growing, yet poorly understood, threat to human wellbeing in South Asia. Major sources of contaminants include untreated industrial effluent, run-off from agricultural land, and naturally occurring toxins such as arsenic and fluoride.

- Although large stocks of fresh water are contained in the alluvial aquifers of the Indo-Gangetic basin, the current rates of groundwater extraction are exceeding recharge rates in some regions (e.g. Punjab, Haryana) and water tables are declining. Prosperity based on this aquifer over-exploitation cannot be sustained indefinitely.

- Flood irrigation of cereal crops, especially rice, is the largest user of water in South Asia. Improved flood irrigation techniques are available (at low or negative cost) that could reduce applied water and increase yield. Nevertheless, much of the applied water runs off or infiltrates, and becomes available for other users.

- There is a large range in agricultural yields and water-use efficiency among South Asian farmers. Agricultural extension services should broadly disseminate best-practice agricultural techniques to farmers, aiming to conserve water and increase yields.

- Perverse incentives to grow crops in inappropriate agro-climatic regions should be ended. Water-intensive crops such as sugarcane and rice should preferentially be grown in water-abundant regions, not in water-scarce regions.

- In regions subject to waterlogging, subsurface drainage systems must be expanded and maintained to avoid reduced agricultural yields. Basin-level accumulation of salt is a long-term challenge, especially in irrigated regions with little rainfall, such as the Indus basin.

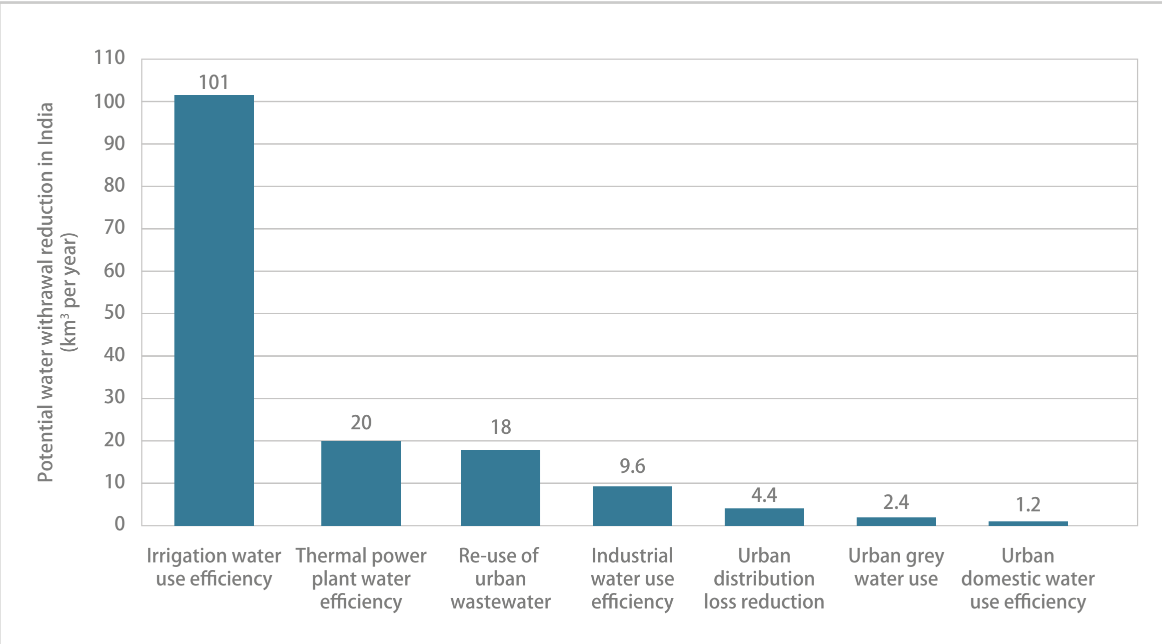

Exhibit 93. Increasing the efficiency of irrigation water use is, by far, the greatest potential technology lever for reducing water withdrawals in India. Other important levers include treatment and reuse of wastewater, and improved water-use efficiency in power plants and industries. Figure shows water withdrawal reductions corresponding to 80% adoption of water-saving technologies. (Source: ITT analysis; see previous sections for details)

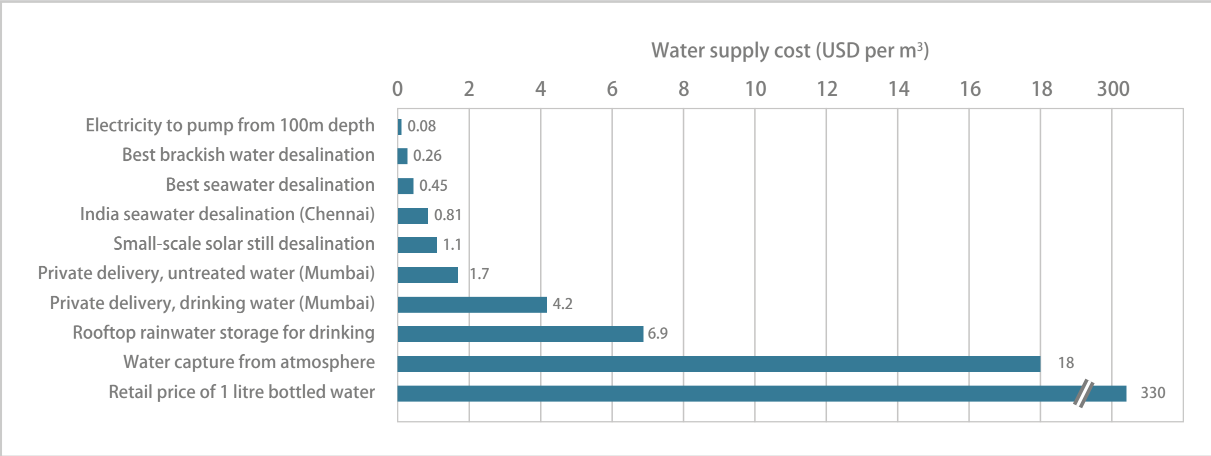

Exhibit 94. Water may be obtained from a variety of sources, with a wide range in cost. This comparison is illustrative, as the quality of the water varies by source. (Source: ITT analysis; see details below)

- Electricity cost to pump water from 100m depth based on typical domestic electricity tariff of USD 0.09 per kWh, and 30% pump set efficiency.
- Best brackish and seawater water desalination based on Shatat & Riffat 2012.
- India seawater desalination based on Chennai bulk water purchase agreement.
- Small-scale solar still desalination cost based on estimated capital cost of 20 USD for 1 m^2 still, 5 L per day fresh water output, and 10-year service life.
- Private delivery of untreated borewell water and treated drinking water based on typical 2017 price in Mumbai.
- Rooftop rainwater storage for drinking based on requirements for 3600 L storage tank (6-month supply of 4 L/capita/day for household of 5 persons) costing 500 USD, with 20-year service life.
- Water capture from atmosphere cost based only on electricity needed to reject the heat of condensation, with coefficient of performance of 3.0, and typical domestic electricity tariff of USD 0.09 per kWh.
- Retail price of INR 20 for 1-litre bottled water based on 2017 typical price in Mumbai.

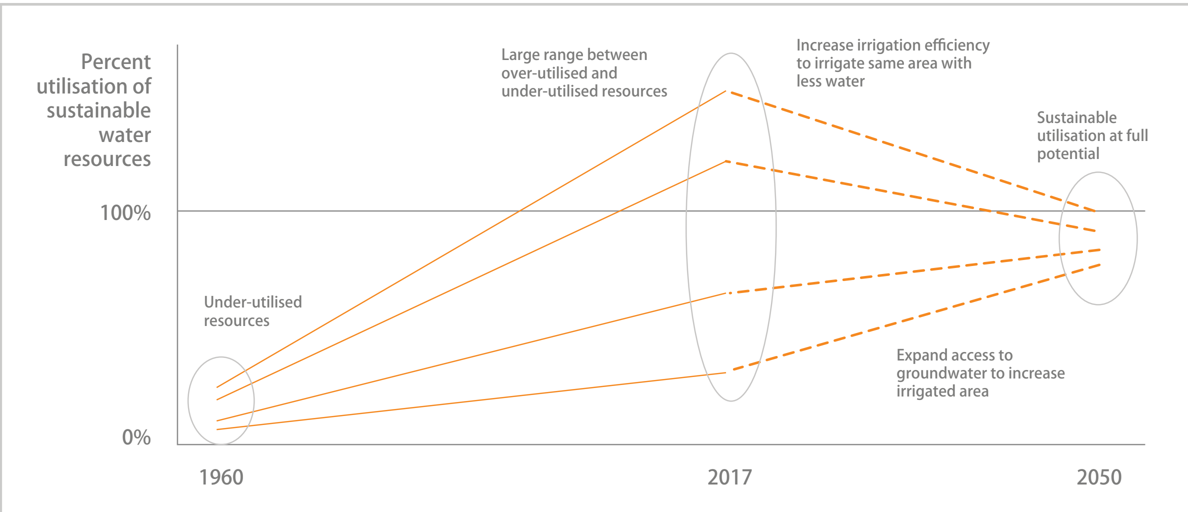

Exhibit 95. As the Green Revolution progressed in South Asia, some regions have over-exploited their water resources. Other regions still do not fully utilise the sustainable water resources potentially available to them. Eventual convergence at full sustainable levels of water utilisation is projected to yield highest long-term human welfare. (Source: ITT analysis)

High	>250 million	Mortality or high livelihood impact	Multiple generations	Extinction	Permanent
Moderate	50-250 million	High morbidity or moderate livelihood impact	~1 generation	Intermediate	Intermediate
Low	<50 million	Moderate morbidity or low livelihood impact	<1 generation	Perturbation	Temporary

Challenge	Human impacts			Environmental imacts	
	Number of people	Severity to health or livelihood	Longevity	Severity	Longevity
3.1 In closed basins, surface water supply is fully utilised and cannot increase	High	Medium	High	High	High
3.2 Groundwater over-extraction in hard rock regions: Limit to water supply rate	High	Medium	High	N/A	N/A
3.3 Groundwater over-extraction in alluvial regions: Water at increasing depths	Low	Low	High	N/A	N/A
3.4 Faecal contamination of water bodies	High	High	Medium	High	Medium
3.5 Chronic diseases from water containing arsenic and fluoride	Medium	High	High	N/A	N/A
3.6 Health impact from diverse industrial effluent and agricultural runoff	Medium	High	Medium	High	High
3.7 Urban water demand from growing cities exceeds local supplies	Medium	Medium	High	Low	High
3.8 Available water supply is becoming brackish or saline	Low	High	High	Medium	High
3.9 Irrigated agricultural land becomes waterlogged and salinized	Low	High	High	Low	High
3.10 Increased flooding during intense storms	Low	High	Low	Medium	High
3.11 Glacier melting is altering the Indus River flow	Medium	Medium	High	Low	High
3.12 Economic water scarcity: lack of means to access sustainable local water	Medium	Medium	Medium	N/A	N/A

Legend: N/A Low Medium High

Table 13. Assessment of the significance of South Asian water security challenges, based on the scale, severity and longevity of human and environmental impacts.

Given adequate political and economic support, what is the technological potential to solve the problem? N/A | low | moderate | high

Technology levers		3.1 In closed basins, surface water supply is fully utilsed	3.2 Groundwater overextraction in hard rock regions	3.3 Groundwater over extraction in alluvial regions	3.4 Faecal contamination of water bodies	3.5 Chronic diseases from water containing arsenic and fluoride	3.6 Health impact from industrial effluent and agricultural runoff	3.7 Urban water demand from growing cities exceeds local supplies	3.8 Available water supply is brackish or saline	3.9 Irrigated agricultural land becomes waterlogged and salinized	3.10 Increased likelihood of flooding during intense storms	3.11 Glacier melting is altering the Indus River flow	3.12 Economic water scarcity: lack of means to access water
6.1 Water end use efficiency improvements	6.1.1 Irrigation efficiency improvements	high	high	high			moderate	moderate		high		high	
	6.1.2 Domestic efficiency improvements	low	low	low				high				low	
	6.1.3 Industrial efficiency improvements	moderate	moderate	moderate				high				moderate	
6.2 Water distribution efficiency	6.2.1 Urban water distribution efficiency	moderate	moderate	moderate				high				moderate	
	6.2.2 Irrigation water distribution efficiency	low	low	low						high		low	
6.3 Metering for management and billing		high	high	high	low		low	high		moderate		high	moderate
6.4 Capture and store rainwater	6.4.1 Small-scale rainwater harvesting		low	low							moderate		low
	6.4.2 Large scale surface water storage		low	low							high		
	6.4.3 Managed aquifer recharging		moderate	moderate									
	6.4.4 Atmospheric water capture												
6.5 Purification of contaminated water	6.5.1 Remove salt from water	low	low	low				moderate	high				
	6.5.2 Kill biological pathogens		low	low	high								
	6.5.3 Remove arsenic and fluoride					high							
	6.5.4 Remove chemical contaminates		low	low			high						
6.6 Identify acess and extract groundwater	6.6.1 Groundwater mapping	moderate	high	moderate		moderate			moderate	moderate			
	6.6.2 Well drilling			low					low	moderate			high
	6.6.3 Water pumping			low					low	moderate			high
6.7 Eliminate pollution sources	6.7.1 Sewage management		low	low	high								
	6.7.2 Industrial effluent management						high						
	6.7.3 Agricultural run-off management						high						
	6.7.4 Manage saline groundwater intrusion		low	low					high				
6.8 Reuse and recycle water	6.8.1 Greywater reuse	moderate						high				moderate	high
	6.8.2 Large scale treatment and reuse	high	high	high	moderate			high				high	
6.9 Inter-basin water transference		moderate	moderate	moderate									
6.10 Drainage management	6.10.1 Sub-surface drainage									high	low		
	6.10.2 Surface drainage									low	high		
6.11 Non-water agricultural factors	6.11.1 Irrigated farming improvements	high	high	high			moderate					high	
	6.11.2 Rainfed farming improvements	high	high	high			moderate					high	

Table 14. Mapping of the technical potential of various technology solutions to South Asian water security challenges, given adequate political and economic support.

Technology levers		Policy	Infrastructure	Human capital	Access to finance	Behavioural change	Existing demand	Market fragmentation	Business model innovation
		Difficulty of deployement							
6.1 Water end-use efficiency improvements	6.1.1 Irrigation efficiency improvements	Medium	Medium	Medium	High	Medium	Medium	High	Medium
	6.1.2 Domestic efficiency improvements	Medium	High	Low	Medium	Medium	High	Medium	Medium
6.2 Water distribution efficiency	6.1.3 Industrial efficiency improvements	Low	High	Medium	Medium	Low	High	Low	Medium
	6.2.1 Urban water distribution efficiency	Medium	Very High	High	Very High	High	High	Low	High
	6.2.2 Irrigation water distribution efficiency	Medium	Very High	Low	Medium	Low	High	Low	Low
6.3 Metering for management and billing		Very High	Very High	Medium	Very High	High	High	Low	Medium
6.4 Capture and store rainwater	6.4.1 Small-scale rainwater harvesting	Medium	Medium	Low	Medium	Medium	Medium	Medium	Medium
	6.4.2 Large scale surface water storage	High	Very High	Medium	High	Medium	High	Low	Low
	6.4.3 Managaed aquifer recharging	High	High	Medium	Medium	Medium	High	High	Medium
	6.4.4 Atmospheric water capture	Very Low	Very High	Low	Medium	Very Low	Low	Medium	Low
6.5 Purification of contaminated water	6.5.1 Remove salt from water	Medium	Medium	Medium	High	Very Low	Medium	Medium	Medium
	6.5.2 Kill biological pathogens	Medium	High	Medium	High	Medium	Medium	Medium	Medium
	6.5.3 Remove arsenic and fluoride	Medium	Very High	Medium	High	Medium	High	Medium	Medium
	6.5.4 Remove chemical contaminants	High	Very High	Medium	Medium	Low	High	Medium	High
6.6 Identify, access and extract groundwater	6.6.1 Groundwater mapping	High	High	Medium	High	Very Low	Medium	Low	Low
	6.6.2 Well drilling	High	Medium	Low	Medium	Low	Medium	Medium	Medium
	6.6.3 Water pumping	Very High	Medium	Low	Medium	Medium	Medium	High	High
6.7 Eliminate pollution sources	6.7.1 Sewage management	High	Very High	Medium	High	High	High	Medium	Medium
	6.7.2 Industrial effluent management	High	High	Medium	Medium	Medium	Medium	Low	Medium
	6.7.3 Agricultural run-off management	High	Medium	Medium	Low	Medium	High	High	Low
6.8 Reuse and recycle water	6.7.4 Manage saline groundwater intrusion	Medium	Medium	Medium	Low	Medium	High	Medium	Medium
	6.8.1 Greywater reuse	Medium	Medium	Low	Medium	Medium	High	High	High
	6.8.2 Large scale treatment and reuse	High	High	Low	Medium	Low	Medium	Low	High
6.9 Inter-basin water transference		Very High	Very High	Medium	High	Medium	High	Low	Medium
6.10 Drainage management	6.10.1 Sub-surface drainage	High	High	Medium	Medium	Medium	Medium	Medium	Medium
	6.10.2 Surface drainage	High	High	Medium	Medium	Medium	Medium	Medium	Medium
6.11 Non-water agricultural factors	6.11.1 Irrigated farming improvements	High	Medium	High	Medium	High	Medium	High	Medium
	6.11.2 Rainfed farming improvements	High	Medium	High	Medium	High	Medium	High	Medium

Legend: Very Low, Low, Medium, High, Very High

Table 15. Mapping of the difficulties of deployment of potential technology solutions for South Asian water security challenges. (See Table 16 for explanation of levels of difficulty.)

	Simple	Feasible	Complex	Challenging	Extremely challenging
Policies	Minimal role of policy/regulation	Low role of policy/regulation	Regulated market with supportive policies	Highly regulated market with policy changes required	Highly regulated and controversial changes required
Infrastructure	Minimal need for infrastructure	Dependent on existing infrastructure	Requires some improvements to existing infrastructure	Requires moderate improvements to infrastructure	Requres major improvements to infrastructure
Human capital	Minimal need for human capital development	Low-moderate need for human capital development	Moderate need to train a limited number of people	Required high level of training for large numbers of people	Requires national scale training programs
Access to user finance	Financing not required	Limited financing required	Moderate financing needed, viable mechanisms available	Significant financing required, limited mechanisms available	Significant finance required, no identified mechanism
Behaviour change	No behaviour change required	Minimal behaviour change required	Moderate behaviour change required with evidence of behaviour change being viable	Major behaviour change required, potentially on daily basis	Significant behaviour change needed on daily basis, changes contrary to cultural norms
Existing demand	Strong existing demand	Existing demand	Moderate demand	Low demand, needs to be built	Extremely low demand or not a perceived need
Market fragmentation/ Distribution channels	Highly concentrated market or well defined channels	Fairly concentrated market and/or well defined channels	Moderate fragmentation of customers, under-developed channels	Fragmented market, weak distribution channels	Highly fragmented, challenging to reach customers
Business model innovation	Clear deployment models existing at scale	Deployment model in process in scaling	Development model(s) being tested	Deployment model(s) being tested, major hurdles outstanding	No identified deployment model, major hurdles identified

Table 16. Five-point scale used in Table 15 to describe the levels of deployment difficulty. For each of the eight categories of difficulties (Policies, Infrastructure, Human capital, Access to finance, Behaviour change, Existing demand, Market fragmentation/ Distribution channels, and Business model innovation), five levels of difficulty are described from Simple to Extremely challenging.

8. TECHNOLOGY IMPERATIVES

The water security challenges facing South Asia are complex and include issues of water quantity and water quality across a range of temporal and spatial scales. Technology interventions comprise a part of a broader solution set, though their effectiveness may be limited by population growth and human tendencies. No single intervention can definitively solve water security problems in the region, but numerous actions can be taken on many fronts to significantly enhance water security.

Several common-sense things must happen to improve the efficiency of water use in South Asia, by implementing current global best practices in multiple sectors, and broadly expanding the use of existing state-of-the-art knowledge. For example:

- Irrigation techniques with high application efficiency, e.g. laser land levelling and tensiometer-based scheduling for flood irrigation of rice and wheat, and deployment of drip and other precision irrigation methods for higher value crops. (see Section 6.1.1)
- Municipal water distribution networks employing modern monitoring and management methods, including metering, pressure management, and leak detection and repair, to overcome problems of intermittent water supply. (see Sections 6.2.1 and 6.3)
- Agricultural extension services for farmers in rainfed and irrigated regions, to employ modern agronomic practices including soil fertility management, integrated pest management and improved seed varieties, to make the best use of available water. (see Sections 6.11.1 and 6.11.2)

Additionally, we identify five important technology imperatives which, if successfully developed and deployed, will significantly enhance water security in South Asia:

1. Scalable sewage treatment systems with energy and water recovery
2. Gene-edited crops with higher tolerance to drought, heat and salinity stress
3. Network of distributed IoT sensors to measure and map water quality
4. Very low cost scalable technique for desalinating brackish water
5. Low-cost well drilling and pumping tools to expand groundwater access

These 5 imperatives are described in detail on the following pages.

1. Scalable sewage treatment systems with energy and water recovery

This imperative calls for the development and deployment of novel sewage treatment facilities that are net sources, rather than sinks, of resources. In energy terms, they should at least operate at net zero energy, but may have the capability to produce usable energy. They should also enable reuse of the treated water for secondary purposes including industrial, recreational, and agricultural applications. The recovery of biological nutrients from sewage may also be a goal. Integrated sewage treatment can be viewed as a way to harvest clean, renewable energy, recover nutrients necessary for agriculture, and close the water loop by appropriately reusing treated wastewater.

Less than 38% of the sewage generated in India is treated before being discharged into water bodies. The amount of resulting sewage in the environment is contributing to India's health problems, including diarrhoeal outbreaks, particularly among children, and lifelong stunting and wasting. The massive organic and nutrient loading has adverse environmental effects and leads to the destruction of ecological productivity of water bodies.

Simultaneously, many growing cities have difficulty meeting the water needs of households and industries, due to physical constraints to water supply manifest as closed river basins and depleting groundwater stocks.

There is a great need for an effective, affordable and scalable sewage treatment method. Conventional wastewater treatment methods are a major resource sink, and it is not advisable to follow the status-quo. In the United States, for example, about 1.3% of all electricity is used for sewage treatment. This is a wasted opportunity, because raw sewage contains about six times more chemical energy than the amount of electrical energy required to treat it.

The chemical energy contained in wastewater can be exploited in several different ways. Methane harvesting from anaerobic digestion is a well-known energy saving and energy producing method. Its drawbacks are its requirements of high concentrations of organic matter, warm wastewater temperatures (i.e. >20 °C), and a high minimum flow rate. Newer energy generation methods include microbial electrochemical technologies, such as microbial fuel cells and microbial electrolysis cells, the use of microalgae for biodiesel, and anaerobic membrane bioreactors, which can produce methane from low concentrations of sewage. Alternative methods include the combined use of micro- and macro-organisms, such as vermicomposting, in which the compost can later be retrieved to recover nutrients.

Important criteria for successful treatment technologies include the extent of land area required, the economic resources needed for capital and O&M, and the quality requirements for the reused water. Land area requirements, in particular, may be an impediment to scale-up of some technologies. This initiative is agnostic to scale, and the technology unit may function at the household, neighbourhood or metropolitan level. Different technology solutions may be appropriate for different settings. Given the secondary usage of the treated water, facilities should be physically located in close proximity to agricultural fields or to city parks for horticultural irrigation. Innovative designs may reduce cost and energy use during treatment, e.g. by employing gravity wherever possible to eliminate pumping.

For more information, see Sections 3.1, 3.2, 3.4, 3.7, 6.5.2, 6.7.1, and 6.8.2.

2. Gene-edited crops with higher tolerance to drought- and salinity-stress

A new generation of crop varieties is needed with tolerance to worsening conditions of drought, heat and salinity in South Asia. Genome editing techniques such as CRISPR/Cas9 have successfully been used to create variants of maize that have higher grain yield under water stress conditions and have no yield loss under well-watered conditions, compared to conventional maize types. Varieties with tolerance to heat and salinity are also expected. Important crops that would benefit from this imperative include wheat, rice and sugarcane.

Agriculture in South Asia will face numerous stressors during the coming decades, such as droughts due to climate change, salinization of farmland and groundwater, and basin-level limits to water supply. Conventional plant breeding techniques are hard-pressed to develop crop varieties to accommodate such rapid changes. A new generation of gene editing techniques has the potential to enable the development of novel crop varieties with enhanced resistance to drought and salinity stresses, allowing continued expansion of agricultural production despite these growing environmental challenges.

Genome editing techniques are capable of precisely and site-specifically (rather than randomly) adding, modifying or deleting genes from plant and animal genomes. Genome editing methods include clustered regularly interspersed short palindromic repeats (CRISPR), zinc-finger nucleases (ZFNs), and transcription activator-like effector nucleases (TALENs) systems. The CRISPR/Cas9 system, in particular, is proving to have many beneficial uses such as increasing crop yield, improving drought tolerance, increasing growth in nutrient-limited conditions, and breeding crops with improved nutritional properties. In this system, the Cas9 nuclease is complexed with a synthetic guide RNA and is delivered into a cell. It then cuts the cell's genome at a desired location, allowing existing genes to be removed and/or new genes to be added.

Hard limits to basin-level water supply exist in hard-rock regions with closed river basins (i.e. much of peninsular India), and many regions are approaching or have exceeded these limits to both surface and ground water supply. Meanwhile, demand for water continues to grow. In these regions, all available annually-renewable water is (or soon will be) fully allocated. CRISPR technology may enable crops that use water more efficiently, producing more biomass per unit of water transpired, to increase total agricultural production in water-stressed basins. An important part of South Asian agriculture does not use irrigation, and instead depends on rainfall for its water needs. While expanding the use of irrigation is possible in some areas, irrigation is constrained in many regions by lack of water sources or excessive economic costs. Using CRISPR technology to make better use of the "green water" that falls on dryland farms, total agricultural production can increase without the need to harness additional water sources.

Importantly, gene editing with CRISPR is cisgenic rather than transgenic modification, meaning that genes are artificially transferred between organisms that could otherwise be conventionally bred. Many consider cisgenic editing to be less controversial than transgenic modification, because the edited organisms could, in principle, have been created through conventional breeding. For this reason, both regulatory procedures and consumer acceptance are proving to be less challenging for cisgenic editing than for transgenic modification. Of more immediate concern may be the asymmetric economic relationship between the producers and planters of edited seeds, as genetically modified organisms have typically been produced and marketed by large multi-national corporations. Structures should ensure that improved seeds are available to all farmers in need, to avoid further widening social inequalities. The production of seeds within South Asia, by existing and emerging biotechnology centres, will provide opportunity for local control. It will also be important to take steps to avoid unwanted second-order environmental effects of edited seeds.

For more information, see Sections 3.1, 3.2, 3.3, 5.5, 6.1.1, 6.4.3, and 6.11.2.

3. Network of distributed IoT sensors to measure and map water quality

There is an urgent need for the development and widespread deployment of IoT (Internet of Things) sensors that detect the levels of the most significant environmental toxins affecting South Asian water, and transmit that information to a platform where it is validated and publicly displayed. Required technological innovations include integrated sensors for the most significant contaminants that are inexpensive enough for mass deployment, as well as a platform for data collection, validation, analysis and dissemination.

Exposure to dangerous environmental toxins is an undesirable side effect of industrialisation in South Asia and elsewhere. Because many toxins are invisible, tasteless and odourless, severe cases of contamination often go undetected and unremedied. Detection of environmental toxins currently requires costly equipment and elaborate sampling protocols, and provides only isolated snapshots of individual places, times and contaminants. To fully understand and solve the problem of environmental toxicity, a more fine-grained knowledge of exposure is required. While we focus on water sensors in this report on water security, we observe that sensor deployment is also needed to assess contamination of air and soil.

Sensors will need to identify and measure three broad categories of pollutants: biological pathogens that are widespread throughout the environment, chemical toxins from both industrial point sources and agricultural run-off, and naturally occurring contaminants including arsenic and fluoride. Key water contaminants to be measured are likely to include:

- Lead
- Mercury
- Arsenic
- Fluoride
- E. coli
- Salinity (measured as Total Dissolved Solids)
- Nitrate (NO_3)
- Polychlorinated biphenyls (PCBs)
- Persistent organic pollutants (POPs)
- Volatile organic compounds (VOCs)

The sensors may be hard-wired and provide continuous monitoring of particular locations, or may be portable to conduct mobile geolocated assessments of contamination. Fixed sensors would likely form the basis of a sensor network, transmitting (continuous or periodic) data to a mapping platform to show changes in quality parameters over time. Issues of sensor performance degradation over time will need to be addressed, to enable robust long-term monitoring. A successful sensor technology will likely not test separately for each individual contaminant, but would scan a water sample and determine quickly and inexpensively its multiple constituents.

Portable sensing by trained staff using mobile devices with disposable one-time sensors could also be useful to increase the spatial density of measurements. Another approach to mobile sensing is "community-based" water quality monitoring, using low-cost portable sensors connected to smartphones that communicate results to the network. This approach may face issues with data reliability due to e.g., incorrect sampling techniques or fraud, so would require additional validation.

For more information, see Sections 3.5, 3.6, 6.5.3, 6.5.4 and 6.7.2.

4. Very low cost scalable technique for desalinating brackish water

This imperative focuses on developing and enabling systems for very low-cost, high-efficiency desalination of brackish water resources, to provide additional freshwater supplies for water-constrained regions to be used by households, industries and farms. The introduction of very low cost desalinated water can enable sustainable irrigation in vast regions of South Asia with brackish groundwater.

Conventional desalination methods typically use seawater as feedwater, and current techniques are approaching the thermodynamic limits of efficiency and have limited opportunity for further improvement. In contrast, there are large potential efficiency gains by using brackish water as feedwater. Costs can be further reduced by matching the salinity of the product water to the salinity thresholds for different use cases; in other words, removing only enough salt to make the water viable for its intended use.

Desalination is increasingly used to provide household and industrial water in regions with scarce freshwater but abundant salt water. Most current desalination facilities are located in the Middle East, use seawater as feed water, and are powered by fossil fuels. The city of Chennai in southern Indian gets about a quarter of its municipal water from reverse osmosis seawater desalination plants. Seawater desalination technologies based on membranes, such as reverse osmosis, are approaching theoretical limits of energy efficiency, and it is unlikely that major technology breakthroughs will fundamentally alter the seawater desalination landscape. Desalinated seawater is too expensive to use as irrigation water for crop production.

For brackish water, however, there are major opportunities for significant reductions in desalination cost and energy use, through innovative electrochemical or other emerging techniques. The minimum theoretical energy requirement for desalination varies with the salinity of the feed water-- less energy is fundamentally needed to desalinate brackish water, compared to seawater. Electromagnetic desalination processes such as electrodialysis (ED) and capacitive deionization (CDI) are limited to low-salinity feed water, but potentially have much lower cost and energy than pressure or thermal techniques. They offer many advantages when used with brackish feedwater, such as high water recovery and high brine concentrations. They also require little or no feedwater pre-treatment, and membrane fouling can be prevented by reversing the electrode polarities. However, electromagnetic processes only remove ions from the water, leaving organics and colloids in suspension-- this is of concern for household water, but less so for irrigation water. Furthermore, the selection and configuration of membranes is currently highly dependent on feedwater characteristics, thus must be adapted to local conditions of feedwater composition and concentration.

Concerted R&D efforts can overcome current obstacles to enable a major source of low-cost freshwater in regions with brackish resources. The appropriate unit scale of desalination facilities may vary, depending on the application (e.g., household, irrigated farm, urban water utility). The salinity of the product water may also vary, depending on the purity requirements of the end uses. Ideally, facilities will be powered by onsite renewable energy sources such as photovoltaic solar arrays, to provide reliable and sustainable operation. Developing appropriate business models will be essential, to ensure economic sustainability and continuing impact. End-uses for the desalinated water will include drinking, cooking, washing and other domestic uses, and industrial water uses. Efficient techniques for large-scale desalination of brackish water resources will also enable the use of desalinated water for production of agricultural crops using efficient irrigation techniques.

For more information, see Sections 3.1, 3.2, 3.3, 3.8 and 6.5.1.

5. Low-cost well drilling and pumping tools to expand groundwater access

This imperative calls for mobilising improved methods to make affordable groundwater wells to ensure access to water in regions facing economic water scarcity.

This problem occurs where the lack of human, institutional, and financial capital limits access to water, even though water is available locally in nature to meet human demands. Some places contain abundant water resources, but some segments of the local populations face water scarcity because they lack the means to access these resources. This may occur in urban and rural areas, and involve drinking, household and irrigation water.

An estimated 80 million farmers in India, cultivating roughly 30 million smallholder farms, are affected by economic water scarcity. In South Asia, physical water scarcity (rather than economic water scarcity) is more commonly felt by households and farmers, though in specific regions there is abundant unutilised groundwater that could be sustainably used for household consumption and to increase agricultural production and economic prosperity. In general, north-eastern Indian states suffer most from economic water scarcity for irrigation. Economic water scarcity for agricultural irrigation is much more common in sub-Saharan Africa where, despite abundant shallow groundwater, communities use low-yielding and highly-variable subsistence rain-fed farming methods. Technology advances made in South Asia could also be used to reduce this economic water scarcity in sub-Saharan Africa.

Well drilling is typically done with portable diesel-powered rigs, which are expensive and have limited mobility to reach remote areas. Numerous manual drilling techniques have been developed, which can produce borewells with less cost, and in locations that would be inaccessible to mechanical drilling rigs. Manual techniques are, however, slow and are limited in the geological strata they can drill. Most current well drilling technologies suffer from high cost, limited portability, slow drilling rate, or limited geologic suitability. To expand groundwater opportunities to rural populations facing economic water scarcity, a drilling technology is needed that combines the speed and capability of powered equipment with the portability and low cost of manual techniques. Such a technology could enable more accessible borewells in regions suffering from economic water scarcity.

Solar powered electric pump sets are under development, which use photovoltaic (PV) arrays to convert sunlight to electricity that then powers submersible or surface-mounted electric pumps. The technology has the potential to significantly scale up in future, as part of a long-term transition toward renewable energy sources. Currently, there are significant barriers to the scale-up of PV-powered irrigation pumps including the high upfront cost of PV systems which are typically 10 times that of conventional pumps (though declining over time as the technology matures). Despite the very low operating costs of PV irrigation pumps, the high capital cost leads to long economic payback times. Experience shows that wealthier farmers have traditionally taken better advantage of subsidies on PV pumps, thus broad-based elimination of economic water security will require reaching the poorest communities.

Since there is zero marginal cost for additional PV water pumping, care must be taken to avoid unrestrained aquifer depletion if the technology is scaled up in the absence of rational water allocation systems. Although over-extraction of groundwater is a problem in many regions of South Asia, other regions of South Asia (and much of sub-Saharan Africa) possess abundant groundwater, yet their populations continue to face economic water scarcity. Major reductions in the cost of well drilling and water pumping could improve the lives of these people, by enabling access to clean water for household and farm use.

For more information, see Sections 3.12, 5.5, 6.6.2 and 6.6.3.

South Asia is "ground zero" for virtually all the world's water security problems. As this study demonstrates, the causes of these problems are truly multi-faceted, and so must be the solutions. Breakthrough technologies can play an important role in addressing these challenges, but only if they are accompanied by thoughtful policies—some common-sense, and others more nuanced. Most importantly, we humans need to rethink our relationship with water, and recognize that it is no longer the infinite resource we could once count on.

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10. PHOTOGRAPHY REFERENCES

Pg 01. A man walks beside a canal in Punjab state, India. Photo by Roger Sathre.

Pg 04. Women in Odisha return home from work in the paddy fields. Photo by Justin Kernoghan of Trocaire, entitled "India 3 Gender 3," is licensed under CC BY 2.0 Source link: https://www.flickr.com/photos/trocaire/10265682234/

Pg 08. The Jhelum River is a tributary of the Indus River and runs through eastern Pakistan into northwestern India. Photo taken by Myasinilyas is in the public domain. Source link:
https://en.wikipedia.org/wiki/Jhelum_River#/media/File:Jhelum_River-Pakistan.jpg

Pg 13. An Indian tubewell. This photo, sourced from USAID's Historical Archive, is available on Wikimedia Commons. Source link:
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Pg 19. Stagnant pollution in Chennai. Photo by Andrew Sorensen, entitled "Serious Pollution," is licensed under CC BY-NC 2.0. Source link:
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Pg 30. Raw sewage flows into the Ganges River below Dapka Ghat in Kanpur. Photo by Daniel Bachhuber, entitled "Waste to the river," is licensed under CC BY-NC-ND 2.0 Source link: https://www.flickr.com/photos/danielbachhuber/3088633058

Pg 33. Young men in Mumbai prepare to defecate in the open. Photo by Seeing Sanitation is licensed under CC BY 2.0 Source link:
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Pg 37. A farmer transplants rice in Bangladesh. Photo by Mike Lusmore/Duckrabbit of WorldFish, entitled "Planting rice in Khulna, Bangladesh," is licensed under CC BY-NC-ND 2.0. Source link: https://www.flickr.com/photos/theworldfishcenter/7253576954

Pg 42. A truck delivers water to households in an urban area . Photo by Sai Madhavi Antharam.

Pg 49. A Pakistani child sleeps on a cot during a prolonged flood. Photo by UNICEF Canada, entitled "Children are the most vulnerable during emergencies," is licensed under CC BY-NC-ND 2.0. Source link:
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Pg 56. A family in Rajasthan collects water from a hand pump. Photo by Save the Children, entitled "Water and Sanitation in India" is licensed under CC BY-NC-ND 2.0. Source link: https://www.flickr.com/photos/savethechildrenusa/5597515441

Pg 61. Rice paddy farmers in Bangladesh. Photo by Mike Lusmore/Duckrabbit of WorldFish, entitled "Planting rice in Khulna, Bangladesh," is licensed under CC BY-NC-ND 2.0 Source link: https://www.flickr.com/photos/theworldfishcenter/7253550038

Pg 67. Rice planting. This photo by CGIAR Climate, entitled "Climate Smart Villages – Karnal," is licensed under CC BY-NC-SA 2.0. Source link: https://www.flickr.com/photos/cgiarclimate/15269300480/

Pg 71. A borewell in Punjab. Photo by Roger Sathre

Pg 77. Several existing technologies have the potential to significantly reduce irrigation water application in South Asian agriculture. On left, a laser land leveller being used on a farm in Haryana, India. On right, a tensiometer installed in a rice field in Haryana, India. These photos by CGIAR Climate are licensed under Creative Commons BY-NC-SA 2.0. The original title of each is "Climate Smart Villages - Karnal." Source links: https://www.flickr.com/photos/cgiarclimate/15269360920/ and https://www.flickr.com/photos/cgiarclimate/15269251919/

Pg 80. A woman in Jaipur uses water sparingly to wash clothes. Photo by Eric Parker, entitled "Water – D7K 1465 ep," is licensed under CC BY-NC 2.0. Source link: https://www.flickr.com/photos/ericparker/6777843310

Pg 123. Young girls collect water in metal vessels. Unhygienic water storage is a major barrier to clean drinking water. Photo by Cecilia Snyder/Heather Arney of WaterPartners International, entitled "Girls carrying water in India," is licensed under CC BY-NC-ND 2.0. Source link: https://www.flickr.com/photos/wateradvocates/1439034081

Pg 134. Example of direct grey water use: a sink in Japan that reuses water for toilet flushing. Photo by Gavin Anderson, entitled "This is what I call grey water usage," is licensed under CC BY-SA 2.0.
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