WATER GLOBAL PRACTICE

Groundwater in Pakistan's Indus Basin

Present and Future Prospects

Lucy Lytton, Akthar Ali, Bill Garthwaite, Jehangir F. Punthakey, and Basharat Saeed

WORLD BANK GROUP

About the Water Global Practice

Launched in 2014, the World Bank Group's Water Global Practice brings together financing, knowledge, and implementation in one platform. By combining the Bank's global knowledge with country investments, this model generates more firepower for transformational solutions to help countries grow sustainably. Please visit us at www.worldbank.org/water or follow us on Twitter at @WorldBankWater.

About GWSP

This publication received the support of the Global Water Security & Sanitation Partnership (GWSP). GWSP is a multidonor trust fund administered by the World Bank's Water Global Practice and supported by Austria's Federal Ministry of Finance, the Bill & Melinda Gates Foundation, Denmark's Ministry of Foreign Affairs, the Netherlands' Ministry of Foreign Affairs, the Swedish International Development Cooperation Agency, Switzerland's State Secretariat for Economic Affairs, the Swiss Agency for Development and Cooperation, and the U.S. Agency for International Development. Please visit us at www.worldbank.org/gwsp or follow us on Twitter #gwsp.

About SAWI

The South Asia Water Initiative (SAWI) is a multi-donor Trust Fund supported by the UK, Australia and Norway and managed by the World Bank. SAWI supports a rich portfolio of activities designed to increase regional cooperation in the management of the major Himalayan river systems in South Asia to deliver sustainable, fair and inclusive development and climate resilience. It does this through four complementary outcome areas: strengthening awareness and knowledge on regional water issues; enhancing technical and policy capacity across the region; dialogue and participatory decision processes to build trust and confidence; and scoping and informing investment designs. Its work, structured across three river basins (Indus, Ganges and Brahmaputra) and the Sundarbans Landscape, spans seven countries: Afghanistan, Bangladesh, Bhutan, China, India, Nepal and Pakistan.

Groundwater in Pakistan's Indus Basin

Present and Future Prospects

Lucy Lytton, Akthar Ali, Bill Garthwaite,
Jehangir F. Punthakey, and Basharat Saeed

WORLD BANK GROUP

1818 H Street NW, Washington, DC 20433
Telephone: 202-473-1000; Internet: www.worldbank.org

Rights and Permissions

Please cite the work as follows: Lytton, Lucy, Akthar Ali, Bill Garthwaite, Jehangir F. Punthakey, and Basharat Saeed. 2021. “Groundwater in Pakistan’s Indus Basin: Present and Future Prospects.” World Bank, Washington, DC.

Cover design: Jean Franz, Franz & Co., Inc.
Cover photos: (left to right) Jay Punthakey, SkycopterFilms Archives/Shutterstock.com, Francois Onimus/World Bank.

Contents

Acknowledgments *viii*
Abbreviations *ix*
Executive Summary *xii*

Chapter 1: The Indus Basin Context **1**
Key Points 1
Introduction 1
Notes 13
References 13

Chapter 2: Groundwater Uses in Pakistan's Indus Basin **15**
Key Points 15
Introduction 15
Groundwater Use in Agriculture 16
Domestic and Municipal Water Uses 20
Industrial Groundwater Use 24
Comparing Sectoral Uses of Groundwater 27
Notes 28
References 28

Chapter 3: Understanding the Groundwater Resource **31**
Key Points 31
Topography and Rainfall 31
Aquifer Overview 32
Water Level and Salinity Trends in the Indus Basin 47
Groundwater Stresses 61
Groundwater Quality in the Indus Basin 74
Notes 83
References 84

Chapter 4: The State of Groundwater Management **89**
Key Points 89
Introduction 89
Policy 90
Development Plans 92
Legal Framework 93
Institutions 96

Groundwater User Groups 99
Monitoring Groundwater Resources in the Indus Basin 101
Notes 104
References 104

Chapter 5: Management Solutions 105
Key Points 105
Introduction 105
Institutional Reform 105
Basin Planning 109
Managing Groundwater Quality 117
Regulatory Instruments 117
Notes 119
References 119

Chapter 6: Conclusions and Recommendations 122
Key Points 122
Conclusions 122
Recommendations 123
Implementation 126

Appendix A: Details of Previous Groundwater Studies in Punjab and Sindh 128
Appendix B: Selected Borelogs in the Indus Basin 149
Appendix C: National Five-Year Plans and Institutional Roles for Groundwater 150
Appendix D: Implementing Recommendations 160

Boxes

E.1. Snapshot of Indus Basin Aquifer Characteristics xvii
1.1. Groundwater Salinity Risks 11
2.1. Groundwater Use in Khyber Pakhtunkhwa 20
3.1. A Detailed Look at Basement Structure of the Chaj and Rachna Doabs 34
3.2. Estimating Pumping in the Rechna Doab 68
3.3. Rechna Doab: Need for Managing Water and Salinity 71
3.4. Seawater Intrusion 72
5.1. Improving Groundwater Management to Enhance Agriculture and Farming Livelihoods in Pakistan 107
5.2. Skimming Wells and Salinity 115

Figures

E.1. Illustration of Changes in Groundwater Level over Time in a Typical Doab in Punjab xv
E.2. Recommendations for Improved Groundwater Management in Pakistan xix
1.1. Pakistan Total Water Demand for 2015 and Projected for 2025 and 2050 4
1.2. Schematic Diagram of Indus Basin Irrigation System 8
1.3. Historical Rise in the Water Table in Punjab 9
1.4. Trend in Groundwater Use in Pakistan 10
B1.1.1. Salinity Risk Enhanced by Pumping 11
2.1. Increase in Number of Tube Wells in the Indus Basin 17
2.2. Percentage of Irrigated Area Served by Different Sources of Water 18
2.3. Yield of Major Crops in the Leading Agricultural Economies 24
2.4. Agricultural Water Productivity in Selected Countries 25
2.5. Projection of Industrial Water Demand in Pakistan for Three GDP Growth Rates 26
B3.1.1. Basement Structure for Rechna Doab 35
3.1. Cross-Section A’-A, through the Upper Reaches of Bari Daob, through Lahore and Kasur. 43
3.2. Cross-Section B’-B through Lower Reaches of Bari Daob through Multan and Lodhran 44
3.3. Cross-Section C’-C through Lower Indus in Qambar Shahdadkot, Larkana, and Khairpur Districts, Sindh 45
3.4. Cross-Section D’-D through Lower Indus in Coastal Districts of Thatta and Badin, Sindh 46
3.5. West to East Cross-Sections Showing Variation in Aquifer Thickness 47
3.6. Depth to Water Table for DLR Bores in Bari Doab 49
3.7. Groundwater Levels in the Khanewal and Sahiwal Divisions, Punjab, 1910-2010. 49
3.8. Depth to Water Table for DLR Bores in Ahmad Pur Sial, Jhang District 50
3.9. Depth to Water Table in Lahore, Multan, Faisalabad, and Sheikhupura 51
3.10. Expansion of the Cone of Depression for the 38-M Drawdown Contour in Lahore from 2007-11 51
3.11. Depth to water table and Electrical Conductivity for DLR bores in Rechna Doab 52
3.12. Depth to water table and Electrical Conductivity in Rechna Doab, June 2008 53
3.13. Conceptual Model of the Indus Basin (West to East) 58
3.14. Indus Basin Average Annual Water Balance 60
3.15. Groundwater Pumped as a Percent of Canal Water 66
B3.2.1. Average Estimated Pumping in Kharif and Rabi Seasons, 2008-13 68
B3.3.1. Salinity EC, October 2012, for 30- to 60-M-Deep Layer for Rechna Doab 71
B3.4.1. Interface between fresh and saline groundwater in coastal areas 73
3.16. Incidence of Water-Borne Diseases in Lower Sindh 78
3.17. Percent of Samples That Were Unsafe for Drinking Water in Sindh, KP, and Punjab, 2015-16 83
4.1. Historical Perspective of Groundwater Development and Management in the Pakistan’s Indus Basin 90
B5.2.1. Skimming Well Design: a) Single Strainer; b) Multistrainer 115
6.1. Recommendations for Improved Groundwater Management in Pakistan 127

A.1. Evaporation from Bare Soil with Water Table at Various Depths 138
B.1. Selected Borelogs in Rechna Doab, Punjab 149

Maps

E.1. The Indus River Basin xiv
1.1. The Indus River Basin 2
3.1. Surface Topography and Elevation of Base of Alluvial Aquifer 33
3.2. Location of Bores Used for Analysis of Aquifer Parameters and the Location of Doabs in the Pakistan Indus Basin 37
3.3. Transmissivity of Indus Basin Alluvium 38
3.4. Hydraulic Conductivity of Indus Basin Alluvium 39
3.5. Specific Yield of Indus Basin Alluvium 40
3.6. Location of Cross-Sections in the Indus Basin through Upper and Lower Sindh 42
3.7. Distribution of SMO Bores for Mapping Depth to Water Table and EC 55
3.8. Water Table Depth and Groundwater Salinity 56
3.9. Average Temperatures in Pakistan 62
3.10. Seasonal Precipitation in Pakistan 63
3.11. Seasonal Potential Evapotranspiration, Jun-Oct 2010-18 64
3.12. Location of Fresh and Saline Groundwater in the Indus Basin of Pakistan 75
3.13. Maps of Spatial Distribution and Values of Selected Chemical Parameters 77
3.14. Arsenic Concentrations Measured in Pakistan Groundwater 79
3.15. Density of Population at Risk of High Levels of Arsenic in Groundwater 80
B5.1.1. 2014 Postmonsoon Depth to Water Table 108
B5.1.2. Depth to Groundwater, Jun 2010 108
A.1. Canal Irrigation Network in Rechna Doab, Punjab, Showing Canal Commands 130
A.2. Lower Bari Doab Showing Irrigation Divisions and Selected Water Courses 131
A.3. Location of Doabs in Punjab 133

Photo

B5.1.1. Measuring Depth to Water Table 107

Tables

1.1. Projected Demand for Water for Agriculture, Domestic, Industry, and Environment 3
2.1. Pakistan’s Population as per Census 2017 and Projections to 2050 16
2.2. Annual Domestic Water Demand and Projections for Urban and Rural Households 21
2.3. Population Growth of Major Cities in Pakistan 22
2.4. Yield Gap (Major Crops) 24
2.5. Historical Water Uses by Sector 26
2.6. UNDP-Pakistan Estimates for Three Water Use Sectors and for Two Scenarios 27
3.1. Groundwater Balance for the Indus Basin in Pakistan 59
3.2. Surface Water Balance for the Indus Basin in Pakistan 59
3.3. Groundwater Storage for the Indus Basin in Pakistan 60

4.1. Key Legislation for Groundwater Management in the Indus Basin 93
4.2. Community-Based Rural Water Supply Tube Wells 100
4.3. Summary of Availability of Groundwater Information and Data 102
5.1. Examples of Regulatory Instruments to Improve Groundwater Management 118
C.1. An Overview of National Five-Year Plans for Groundwater Management 150
C.2. Roles and Responsibilities of Groundwater-Related Institutions 152
D.1. Supporting Priorities, Strategic Actions, Outcomes, and Suggested Performance Measures for Sustainable Groundwater Management 161

Acknowledgments

This report was prepared by a World Bank team led by Lucy Lytton, with contributions from Bill Garthwaite and Basharat Saeed. In producing the report, the team relied on commissioned technical work delivered by Ecoseal Developments Pty Ltd, specifically Dr. Jehangir F. Punthakey and Dr. Akthar Ali.

Peer review was provided by Mohammed Umer Karim (FAO) and World Bank colleagues Francois Onimus and Winston Yu.

Assistance with technical revision was provided by Jude Cobbing. Editorial assistance and publishing support were provided by Erin Barrett, Hiromi Yamaguchi, Ayesha Mehmood, Neha Ravail Abdul Khaliq and the map clearance team.

This is a technical assistance project (P167253) under the SAWI Indus Basin Focus Area.

The South Asia Water Initiative (SAWI) is a multi-donor trust fund supported by the U.K., Australia, and Norway and managed by the World Bank. SAWI supports a rich portfolio of activities designed to increase regional cooperation in the management of the major Himalayan river systems in South Asia to deliver sustainable, fair, and inclusive development and climate resilience. It does this through four complementary outcome areas: strengthening awareness and knowledge on regional water issues; enhancing technical and policy capacity across the region; dialogue and participatory decision processes to build trust and confidence; and scoping and informing investment designs. Its work, structured across three river basins (Indus, Ganges, and Brahmaputra) and the Sundarbans Landscape, spans seven countries (Afghanistan, Bangladesh, Bhutan, China, India, Nepal, and Pakistan).

Abbreviations

ACIAR	Australian Centre for International Agriculture Research
AEM	airborne electromagnetic
AIIB	Asian Infrastructure Investment Bank
ASL	Above sea level
BCM	billion cubic meters
BRBD	Bambanwala-Ravi-Bedian Doab
CAPEX	capital expenditure
CBO	community-based organization
CCA	cultivable command area
CCI	Council of Common Interests
Cfs	cubic foot per second
CGWB	Central Ground Water Board
CSIRO	Commonwealth Scientific and Industrial Research Organization
CTW	community tube well
DLR	Directorate of Land Reclamation
DRIP	Drainage and Reclamation Institute of Pakistan
EC	electrical conductivity
ET	evapotranspiration
FAO	Food and Agriculture Organization
FATA	Federally Administered Tribal Area
GCA	gross command area
GCM	general circulation model
GCISC	Global Change Impact Studies Center
GDAS	Global Data Assimilation System
GDP	gross domestic product
GRACE	Gravity Recovery and Climate Experiment
Ha	hectare
IBIS	Indus basin irrigation system
IUCN	International Union for Conservation of Nature
IWASRI	International Water Logging and Salinity Research Institute
IWMI	International Water Management Institute
IWRM	integrated water resource management
K	hydraulic conductivity
KFE	Khairpur Feeder East
km	kilometer
KP	Khyber Pakhtunkhwa
LBDC	Lower Bari Doab Canal

LBDCIP	Lower Bari Doab Canal Improvement Project
LBOD	Left Bank Outfall Drain
LCC	Lower Chenab Canal
LIP	Lower Indus Project
lppd	liters per person per day
MAF	million acre-feet
MAR	managed aquifer recharge
MARVI	Managing Aquifer Recharge and Sustainable Groundwater Use through Village-Level Intervention
mASL	meters above sea level
me/l	milliequivalents per liter
MCM	million cubic meters
Mha	million hectare
MNFSR	Ministry of National Food Security and Research
MOWR	Ministry of Water Resources
MPDR	Ministry of Planning, Development and Reform
MSL	mean sea level
NAQUIM	National Project on Aquifer Management
NASA	National Aeronautics and Space Administration
NGO	nongovernmental organization
NOAA	National Oceanic and Atmospheric Administration
NRSP	National Rural Support Program
OFWM	on-farm water management
OPEX	operating expenditure
PAH	polycyclic aromatic hydrocarbon
PARC	Pakistan Agricultural Research Council
PHED	Public Health Engineering Department
PC	Pakpattan Canal
PCRWR	Pakistan Council of Research in Water Resources
PID	Punjab Irrigation Department
PIDA	Punjab Irrigation and Drainage Authority
PSDP	public sector development program
PTW	private tube well
RSC	residual sodium carbonate index
SAR	sodium adsorption ratio
SCARP	Salinity Control and Land Reclamation Project
SID	Sindh Irrigation Department
SIDA	Sindh Irrigation and Drainage Authority
SMO	SCARP Monitoring Organization
SRTM	Shuttle Radar Topography Mission

STW	SCARP tube well
Sy	specific yield
TDS	total dissolved solids
TMA	Tehsil Municipal Administration
UNDP	United Nations Development Programme
UNICEF	United Nations International Children’s Fund WAPDA Water and Power Development Authority
WASA	Water and Sanitation Agency
WHO	World Health Organization
WRIS	Water Resources Information System
WWF	World Wide Fund for Nature

Executive Summary

> *But now a water crisis is descending like a thunderbolt.*[1]

An Unfolding Crisis

Groundwater is arguably the most poorly understood water resource in Pakistan—a country in which matters of water resources are hotly debated on a regular basis. Groundwater has the potential to be the most reliable water resource for Pakistan, providing a buffer against the unpredictability of climate change and the failure of infrastructure designed to deliver surface water. The path to sustainable management of groundwater resources first requires a much better understanding of the resource, starting with its geological home: the Indus basin aquifer, the subject of this report carried out by the World Bank with funding from the South Asia Water Initiative.

The Indus basin groundwater aquifer in Pakistan holds in storage at least 80 times the volume of fresh water held in the country's three biggest dams. In the 1960s, large-scale extraction from this underground storage began and has expanded to become an essential input to agriculture and the backbone of domestic water provision. Yet in 2020, Pakistan is on the brink of a lengthy and severe groundwater crisis.

The decades of groundwater development in Pakistan that have elevated groundwater to its current significance have unfolded with minimal management or regulation of the resource. The supply of safe, usable groundwater is diminishing as a result of pollution, overextraction, poor management of canal water, and inappropriate irrigation practices. Despite decades of national and international experts predicting the burgeoning crisis and identifying key requirements to address these challenges, little attention has been given to them. As a result, depletion is curtailing feasible access to groundwater in Punjab, and waterlogging and salinity continue to threaten water and soil quality in Sindh.

Pakistan lacks a comprehensive, reliable system for measuring groundwater extractions and their impact on the resource base. The limited investments in measurement that have been made have lacked coordination and been too sparse and infrequent to allow for comprehensive mapping and monitoring—the measurement or control of water quality even less so. Thus, the ability to steer groundwater use toward sustainability and tackle new challenges is compromised.

In the face of rising population, the effects of climate change, and the considerable natural lag in groundwater response to management interventions, the failure to tackle these challenges is already impairing national water security and drinking water quality. Unchecked, they will lead to a sharp decrease in water security, rising costs for the treatment of drinking water, and a pathway to poverty for a significant number of the rural population.

Groundwater: The Backbone of Rural Prosperity

Groundwater use in the Indus basin in Pakistan has steadily grown since the 1960s, and it now supports more than half the irrigation requirements in Punjab and as much as 20 percent of the irrigation requirements in Sindh. Total groundwater withdrawals are estimated to be 62 billion cubic meters per year, about one-third of the total annual water withdrawal in Pakistan.

The contribution of groundwater to agriculture is substantial. Access to it has enabled farmers to compensate for shortfalls in canal water delivery, increase cropping intensity, and adapt to increasing rainfall variability. The ability to pump fresh groundwater on demand has also enabled tail-end famers to partially mitigate inequity in surface water distribution. For rural households, it has been an invaluable driver of improved livelihoods and food security. For Pakistan, it has underlain decades of growth and development.

And the Source of Most of Pakistan's Drinking Water

More than 70 percent of Pakistan's drinking water comes from groundwater, with most rural households accessing water through handpumps, motorized pumps, and manually from wells. Most of the major cities in Pakistan rely on groundwater for domestic supplies, as do 90 percent of rural households in Punjab and Sindh.

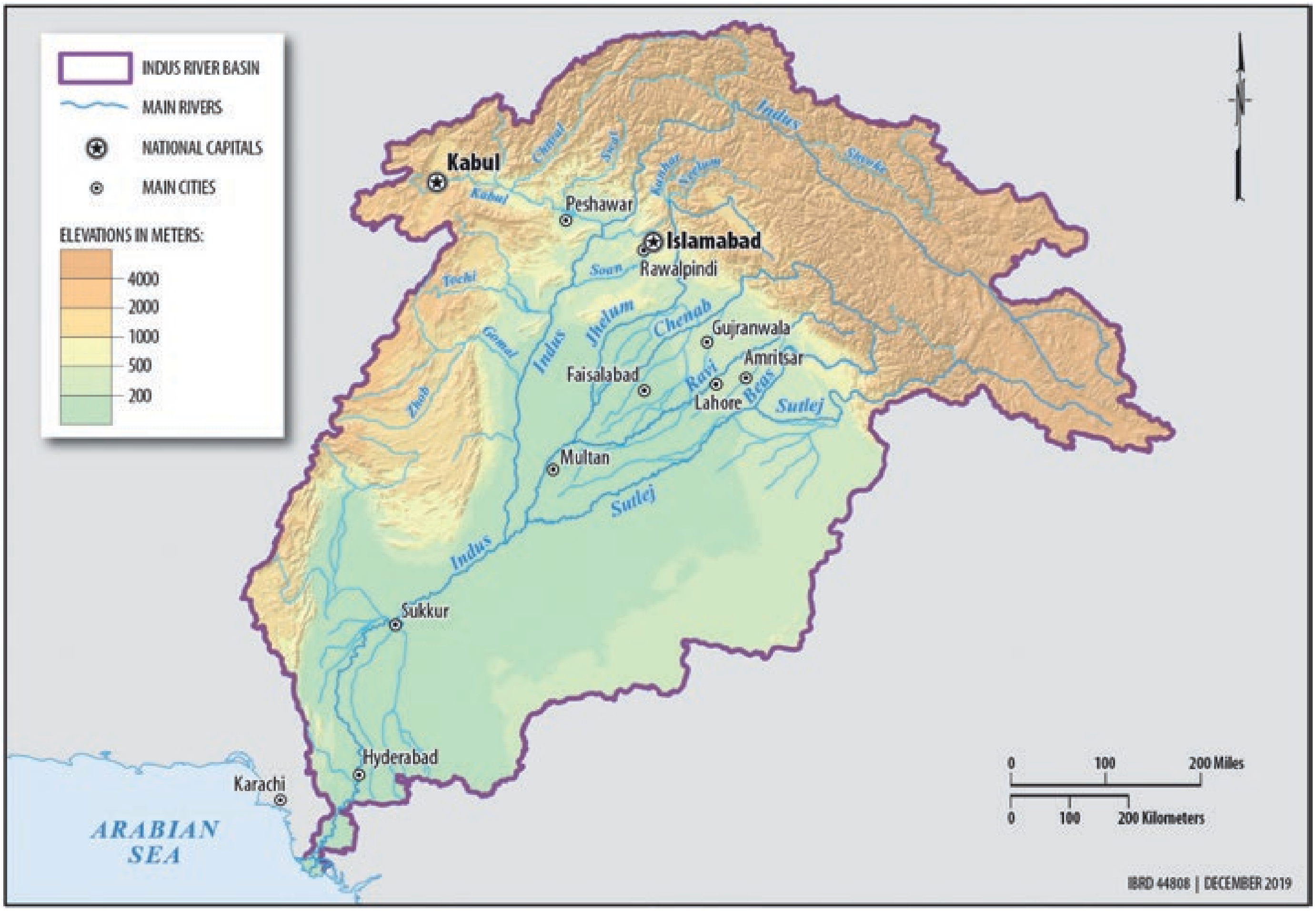
The Indus Basin Aquifer: A Transboundary and Multisectoral Resource

The Indus River basin is home to more than 300 million people across Afghanistan, China, India, and Pakistan (see map E.1). Nearly half the basin lies in Pakistan, where it covers about two-thirds of the country's land mass and is home to nearly 183 million people, about 87 percent of Pakistan's population. The Indus basin is the heartland of irrigated agriculture in Pakistan, supported by the largest contiguous irrigation network in the world, and accounts for 96 percent of the country's total renewable water resource.

The Indus basin irrigation system (IBIS) consists of a network of dams, barrages, and canals built in stages from the early 1900s. An unintended outcome of this vast surface water delivery system is that a significant volume of seepage water has been introduced into the underlying groundwater system, which now represents the largest reservoir of freshwater in the country and constitutes a transboundary resource of major importance. Conservatively estimated at 1,250 billion cubic meters, the fresh groundwater in storage in this aquifer represents less than 13 percent of the total 10,000 billion cubic meters stored in the aquifer, the remainder being brackish or saline, which, for most purposes, is not usable without treatment.

Before the development of the irrigation network, groundwater in the Indus basin is considered to have been relatively deep and saline, except for narrow zones adjacent to the rivers that cross the Indus plain. Seepage from the expanding canal network became the major source of groundwater recharge and led

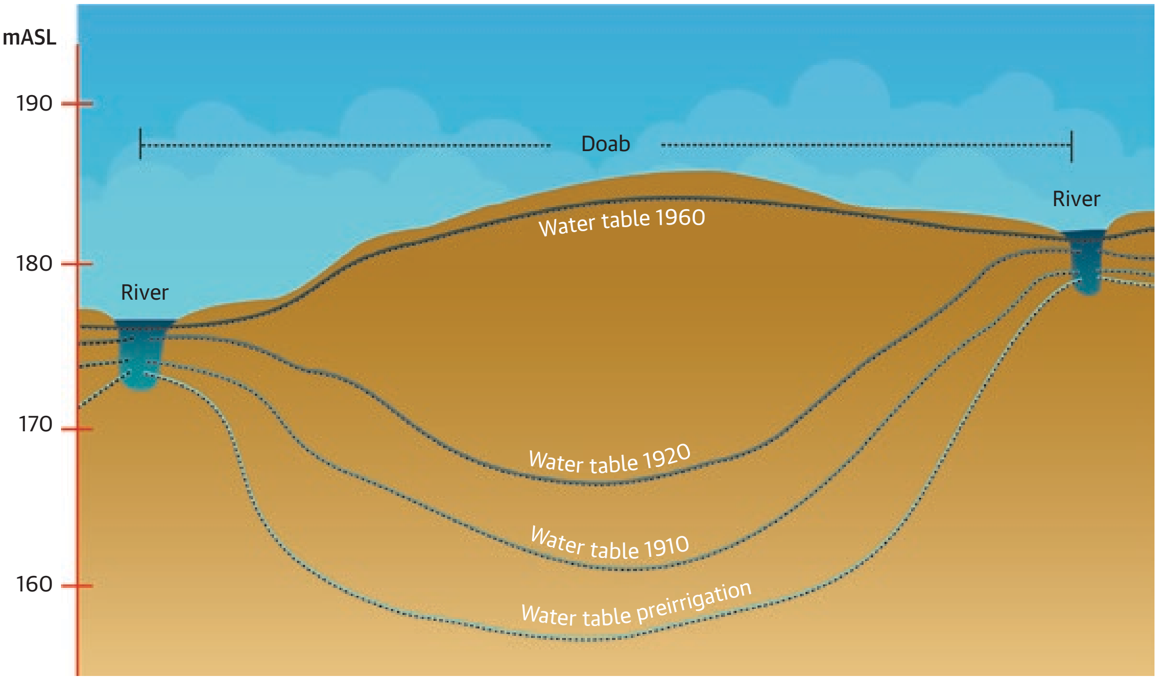
MAP E.1. **The Indus River Basin**



to the buildup of a thick layer of fresh groundwater on top of the underlying saline groundwater and a steady rise in the water table (see figure E.1) over time. By the 1960s, this had given rise to the problem of widespread waterlogging and associated secondary salinity.

Extensive groundwater pumping first started in the Indus basin in the 1960s, partly as a drainage solution with the objective of lowering the water table to reduce waterlogging and land salinization. The value of groundwater as a year-round reliable source of water soon became evident and led to a rapid expansion of its use for irrigation—and a general uncontrolled increase that lasted for decades. The impact of this continued expansion in groundwater use was evident by the mid-1990s, and now this trend threatens the resource itself as unsustainable pumping leads both to the depletion of the resource and the risk of salinization by drawing in saline water from deeper groundwater and from adjacent salty groundwater (located in those parts of the aquifer farthest from sources of recent recharge).

FIGURE E.1. **Illustration of Changes in Groundwater Level over Time in a Typical Doab in Punjab**



Source: Adapted from Greenman et al. 1967.
Note: mASL = meters above sea level.

Turning back the clock on groundwater use through blanket restrictions or large-scale decommissioning of infrastructure is not possible as households have come to rely on groundwater over time as a strategy for ensuring domestic water access, food security, livelihood sustainability, and climate change adaptation, especially in Punjab and Sindh.

Groundwater use has made it possible for farmers to buffer the unreliability of surface water supply and timing, which has worsened over recent decades, and enabled them to increase cropping intensity, thereby improving their livelihoods and food security. It has helped to mitigate the inequity in surface water distribution, which is typical of poorly managed gravity-based systems, such as the IBIS, by allowing farmers at the tail end of canals to compensate for the shortfalls in their allocated share of surface water. Lastly, access to groundwater for irrigation has helped farmers adapt to increasing variability in precipitation in areas where crop rotations are fully or partially dependent on direct rainfall. In irrigated areas where canal operational schedules have not adapted to changing sowing and harvesting calendars—another manifestation of climate change—access to groundwater provides an essential buffer.

In Punjab, locally high rates of pumping have led to falling water tables and significant groundwater depletion in some areas, particularly in large parts of rural eastern Punjab and in areas of high urban use, such as Lahore. As tube wells are sunk deeper and deeper to satisfy the ongoing need for water in these areas, the risk of groundwater salinization increases.

In Sindh, high canal levels, large irrigation return flows, and naturally poor drainage all support high water tables that lead to waterlogging and the buildup of soil salinity. Waterlogging affects substantial areas of Sindh, as does secondary salinization resulting from evaporation from the waterlogged areas. In the absence of drainage, mitigation options are limited as the shallow water tables restrict the ability of the aquifer to store fresh recharge from rainfall and floodwater. In coastal areas, salinity from marine intrusion poses an additional threat, arising principally from the rise in sea level associated with climate change.

The important contribution of groundwater to domestic water supply has already been stated. Most of this domestic water in both rural and urban Pakistan falls short of basic health standards, especially for drinking purposes, and many parameters are not routinely measured. This compromised water quality has significant public health outcomes, inevitably having a disproportionate effect on the most vulnerable households. These households have no choice but to continue to pump groundwater for their domestic use, despite its poor quality, because they lack access to piped water and cannot afford alternative forms of water supply.

How Well Are Groundwater Resources Understood and Managed?

The myriad challenges confronting groundwater use in Pakistan are extensively discussed in the media, civil society discourse, and public policy deliberations. But this broad awareness of the importance of groundwater is not accompanied by a broad understanding of the topic and has not led to investments in obtaining a better understanding of the resource itself—or to improved efforts to manage it. Groundwater monitoring and management is a provincial responsibility, but measurements are at best infrequent and unreliable, and responsibility appears fragmented among agencies. Groundwater levels and salinity are measured only twice a year in the canal command areas of Punjab (previously also in Sindh), nominally pre- and post-monsoon. This low frequency of data collection does not allow a detailed analysis of the main drivers of groundwater behavior, and some measurements lack authenticity. Groundwater withdrawals are not measured. Estimated at 62 billion cubic meters per year, they are in excess of estimated annual groundwater recharge from all sources, but there is considerable local variation.

Public programs for groundwater management have been conducted primarily on a project basis, and in response to specific problems, such as the widespread problems of waterlogging and salinization in the 1960s. These projects were conducted by federal agencies, such as the Water and Power Development Authority (WAPDA) and the Pakistan Council of Research in Water Resources (PCRWR). While these agencies continue to conduct ad hoc regional and local studies on groundwater, these do not contribute to perceptible management actions. The extent to which groundwater measurement is conducted by

BOX E.1. Snapshot of Indus Basin Aquifer Characteristics

Groundwater in the Indus basin is held in thick deposits of mainly fine to medium sand, silt, and clay, with minor gravels. Although there is a tendency for these sediments to become finer in a southerly direction, there is significant heterogeneity in the distribution and extent of individual sediment layers. These variations give rise to local characteristics in terms of quality, flow velocity, storage capacity, and accessibility and have led to a marked distinction between the provinces of Punjab and Sindh. Local characteristics become important for groundwater resource management, requiring extensive monitoring to comprehensively understand the resource—and a high level of localized intervention in order to manage it.

provincial or federal agencies varies, as does the degree of planning and coordination of all activities, both among sectors and across levels of government, within provinces, and among jurisdictions.

Groundwater resources of Pakistan are poorly understood, both at the basin level and at the level of local administrative units where most water-related service delivery functions are vested. The existing knowledge base is sufficient, however, to paint a broad and static picture of aquifer characteristics along with its regional implications (see box E.1), but the limited scope and scale of groundwater measurement preclude the possibility of sophisticated groundwater management and regulation. Waterlogging, depletion, and salinization are shown to be linked problems that require a holistic management approach. This is for the management of not only water volumes but also water quality—salinity, as referred to earlier, and naturally occurring contaminants, such as arsenic and fluoride, and pollutants introduced by human activity. The shallow nature of groundwater in the Indus basin renders it vulnerable to poor land use practices, including the overapplication of agricultural chemicals and fertilizers, inadequate construction and management of water and sanitation facilities, the inappropriate discharge of domestic and industrial effluents, and the mismanagement of solid waste.

Across the Indus basin in Pakistan, poor enforcement of environmental regulations, low investment in wastewater treatment, and unmanaged and unlicensed expansion of pumping infrastructure have contributed to an increase in groundwater contamination from industrial, domestic, and natural sources. Policy actions too have been tardily applied and curative (that is, intervening when the situation becomes untenable) rather than preventive (that is, intervening in time to ensure sustainable use).

The lack of good-quality, frequent, reliable, and accessible data on Pakistan's groundwater resources severely constrains the supply of information to decision makers and consequently makes groundwater management more difficult. With predicted increases in demand for water, particularly in urban areas, and the likely effects of climate change, the need for reliable and representative groundwater data will increase.

Groundwater in Pakistan's Indus Basin: Is There an Expiration Date?

Currently, the total renewable freshwater available per person in Pakistan is estimated to be 1,100 cubic meters per year. Although this is substantial, Pakistan is becoming increasingly water insecure as a result of the poor economic, social, and environmental outcomes it derives from its water resources, including groundwater. Population growth, demographic changes, and climate change will only increase demand for water throughout the economy. Population growth alone will reduce freshwater available per person to 900 cubic meters per year by 2050. Although relative increases for industrial and domestic demand are predicted to outstrip those for irrigation water, agriculture, which accounts for most consumption of water, will still boast the largest absolute increase in demand. Cumulatively, total projected demand will exceed available water supply by 2047, unless substantive sector reforms are undertaken, and substantial investments are made in demand management.

It is clear that, because of past mismanagement and anticipated future stresses, the present approach to groundwater in Pakistan is unsustainable. Failure to act immediately will further deteriorate groundwater quality and quantity, the effects of which will be felt for many generations and risk contributing to a decline in economic prosperity and health outcomes for the nation.

Groundwater under Threat: How Can Pakistan Respond?

The National Water Policy 2018 identifies specific objectives for groundwater, mostly related to improving knowledge of groundwater resources and identifying and managing groundwater quality. The policy also indicates increasing responsibility for provinces and local institutions. Water policy frameworks are being developed at the provincial level, and legislation is being drafted that includes groundwater as a defined component of provincial water resources, a recent example being the Punjab Water Act 2019. The challenges that Pakistan faces in managing groundwater are significant, but this is not a unique situation in the region. National, regional, and international examples demonstrate ways of tackling each of the identified challenges.

The first requirement is a policy framework and enacted legislation that support the implementation of institutional reform and resource management. Following this, a selection of solutions is available to Pakistan, which can be adapted to local realities. This is based on key principles of water resources management, experiences from basins with similar geological and hydrological profiles, and practices from countries with a similar institutional history of groundwater management.

Regional and national examples of institutional reform and resource planning provide an indication of approaches that may be applicable across Pakistan's Indus basin:

- In India:
  - Responsibility for groundwater monitoring and management is vested in state (provincial) governments. Federal institutional and technical support is provided through the Central Ground Water Board (CGWB) within the federal water resources ministry.
  - Under the national groundwater management improvement program (Atal Bhujal Yojana), commenced in March 2020, community participation is at the center of developing water budgets at the block level.
- In Pakistan:
  - An example in three provinces is provided by a project (*Improving Groundwater Management to Enhance Agriculture and Farming Livelihoods in Pakistan*) supported by the Australian Centre for International Agricultural Research (ACIAR), which treats farmers as researchers, so they are integral to data collection, analysis, and decision making.

Institutional reform and resource planning are complex tasks anywhere in the world and require coordination across multiple stakeholders and sectors. Given the state of groundwater management in Pakistan and the country's federal structure, interventions at multiple tiers are required. Based on the current understanding of the Indus basin aquifer and the challenges faced by Pakistan, management recommendations fall into four main areas, as shown in figure E.2, each of which requires consideration at various levels of policy, practice, and governance. Every action within each of these components represents an important advance along the road map to reform.

FIGURE E.2. **Recommendations for Improved Groundwater Management in Pakistan**

Institutional reform and regulation

- Appoint provincial lead agencies and agree on scale of management
- Regulatory reform
- Interim management arrangements
- Stakeholder/community engagement

Conjunctive management, waterlogging, salinity, and depletion

- Develop water budgets for management areas
- Closely monitor water balance to ensure irrigation deliveries do not exceed drainage capacity
- Demand management and managed aquifer recharge
- Stakeholder/community engagement

Data for integrated basin planning and resource modeling

- Lead agency responsible/accountable for data
- Structured capacity building and development of data architecture
- Consolidated surface water and groundwater data (static and dynamic data)
- Data sharing with managers and users

Managing groundwater quality

- Identification of local water quality parameters and regular water quality monitoring
- User participation to monitor and control land use practices and effluent disposal
- Treatment of drinking water
- Data sharing with managers and users

Institutional Reform and Regulation

Groundwater management cannot progress in Pakistan without institutional accountability for it. As resource management responsibility lies with the provinces, it is appropriate for accountability to rest with lead agencies at the provincial level. Federal support will be important in such key areas as setting national standard and policies and supporting capacity building, as well as fulfilling an important role in transboundary (domestic and international) discussions.

Institutional strengthening should reflect the scale at which the resource will be managed (such as canal command area) and include stakeholders and communities affected by management decisions. Because of the importance of conjunctive use in the Indus basin, canal resources and groundwater resources need to be managed together, which means that departments managing the canal resources (primarily the provincial irrigation departments) also need to be reformed to accommodate this requirement. The criticality of water to the health of all sectors indicates the importance of effective coordination among sectors and levels of government.

A variety of regulatory measures (for example, metering, tariffs, asset registration, and limits on agrochemical use) are needed to assist in groundwater management, specifically to rationalize use and to protect quality.

Data for Integrated Basin Planning and Resource Modeling

As there is now a national water policy to provide the principles and impetus for reformed water management, Pakistan has a unique opportunity to develop a strategy for improved groundwater data that puts provincial institutions in the forefront and ensures federal support.

To support water resource planning, and as part of the institutional reform, ownership and accountability for monitoring and managing the resource should be assigned to a lead agency at the provincial level. The lead agency in each province will be accountable for data integrity and the establishment of an information management system. The federal government can support this by facilitating a structured and continued capacity-building program and helping to establish suitable data architecture and communities of practice. The regular involvement of research institutions is recommended to ensure the long-term integrity and management of data.

Conjunctive Management, Waterlogging, Salinity, and Depletion

Formal management principles can be applied to existing conjunctive use practices to achieve more effective and equitable utilization and distribution of water resources, as well as to address the imbalances that are occurring across provinces and leading to depletion of groundwater resources and waterlogging.

Conjunctive management requires the effective management of the water balance at the level of canal command, ensuring that irrigation deliveries do not exceed the drainage capacity (natural or enhanced) of the irrigated area. This requires a good understanding and close monitoring of water inflows and outflows. In addition to the drainage wells installed under the Salinity Control and Reclamation Project and the Left Bank Outfall Drain, many local approaches have been tried or proposed already in Pakistan.

These include skimming wells, scavenger wells, biosaline agriculture, and conjunctive management. They show promise but have not been maintained or lack extensive application.

The first steps in groundwater management in the Indus basin were part of efforts to control waterlogging and salinization, but the success in Punjab was not replicated in Sindh. These approaches need to be revisited and adapted to the ongoing waterlogging in Sindh with a focus on drainage works in the context of regional aquifer characteristics. By contrast, the overextraction of groundwater in Punjab must be approached by controlling groundwater demand and enhancing recharge. Across the Indus basin, the problem of groundwater quality must be taken seriously to enable this resource to provide safely more than 70 percent of Pakistan's drinking water without incurring exorbitant treatment costs.

No solution, or suite of solutions, will achieve effective groundwater management, water budgeting, or basin planning in Pakistan without demand management. This is particularly the case for areas facing depletion. Facets of demand management include crop choice, irrigation control and improvements to water productivity, and regulatory control.

Although supply-side solutions, such as managed aquifer recharge (MAR), can provide reprieve in areas in which groundwater depletion is a serious problem, it comprises a package of important technical components and favorable conditions necessary for success without adversely affecting other water users.

Managing Groundwater Quality

Managing groundwater quality poses a significant challenge as it entails measuring and tracking the occurrence and source of contaminants, treating the water, or remediating the host aquifer. It is recommended that a risk-based approach be adopted to manage groundwater quality. This will help to prioritize actions, such as control of the pollution (stopping the source) and management once it has occurred. Working with stakeholders and regulators to control land-use practices and effluent disposal are critical elements to arresting and managing groundwater contamination. If groundwater for drinking purposes is already contaminated, solutions include the deployment of alternative water sources and installing treatment facilities. Because groundwater quality problems can be quite localized, important components of a groundwater quality management strategy are the initial identification of water quality parameters of concern, their sources, and ongoing monitoring to track trends.

Why This Report?

In 2019, the World Bank published a water security diagnostic report for Pakistan titled *Pakistan: Getting More from Water* (Young et al. 2019). One of the recommendations for making Pakistan water secure was to "adopt conjunctive planning and management of surface and groundwater," with the strategic objectives of maximizing the use of aquifer storage, ensuring sustainable groundwater use, improving equity in water access, and reducing waterlogging and salinization. Pakistan's National Water Policy 2018 includes a dedicated chapter on groundwater, which recognizes the need to improve knowledge of groundwater resources and uses, as well as to identify and manage groundwater quality. The policy reaffirms the need to address the technical challenges of waterlogging, salinization, and depletion and the institutional responsibility of provincial governments to manage groundwater.

The objective of this report is to pursue the spirit of these recommendations and assist the government of Pakistan to address groundwater management challenges in the Indus basin by identifying paths to reform and a program of investments. It identifies both natural and anthropogenic factors that affect the temporal and spatial variability in the availability and quality of groundwater across the Indus basin; outlines the risks to many sectors posed by the ongoing failure to adequately measure and manage the resource; provides examples of targeted management interventions drawn from local, regional, and international settings; and proposes institutional reforms and essential management interventions that can be introduced over a span of years, leading to the long-term viability of the resource. This report provides a holistic view of groundwater resources across the Indus basin in Pakistan with a particular focus on Punjab and Sindh.

None of the management objectives highlighted in this report can be achieved without accurate and representative monitoring data, a regulatory and compliance approach that addresses the full spectrum of activities affecting groundwater, and a commitment to scientific and technical excellence that extends from the early years of education to the peak of civil service career positions.

The work for this report was completed just before the global outbreak of the COVID-19. As policy makers struggle to respond to this crisis, it is worth keeping in mind that the agriculture sector employs nearly half of the labor force, providing a livelihood to most of the rural population. Groundwater provides 90 percent of rural and more than 70 percent of urban household water needs. In terms of employment potential and hygiene requirements, the objectives of sustainable groundwater management and those of responding to the COVID-19 crisis can be met at the same time and, in some cases, by conducting the same activities.

The provision of safe water, sanitation and hygienic conditions is essential to protecting human health during all infectious disease outbreaks, including of coronavirus disease (COVID-19).[2]

Notes

1. *National Water Policy 2018.* Ministry of Water Resources, Government of Pakistan, Islamabad. https://mowr.gov.pk/wp-content/uploads/2018/06/National-Water-policy-2018-.pdf.
2. WHO (World Health Organization) and UNICEF (United Nations Children's Fund). 2020. "Water, Sanitation, Hygiene, and Waste Management for the COVID-19 Virus." Interim Guidance note April 23, 2020. https://apps.who.int/iris/bitstream/handle/10665/331846/WHO-2019-nCoV-IPC_WASH-2020.3-eng.pdf

References

Greenman, D. W., W. V. Swarzenski, and G. D. Bennett. 1967. "Ground-Water Hydrology of the Punjab, West Pakistan with Emphasis on Problems Caused by Canal Irrigation." Geological Survey Water-Supply Paper 1608-H, U.S. Department of the Interior, Washington, DC.

Young, W. J., A. Anwar, T. Bhatti, E. Borgomeo, S. Davies, W. R. Garthwaite, E. M. Gilmont, C. Leb, L. Lytton, I. Makin, and B. Saeed. 2019. "Pakistan: Getting More from Water." Water Security Diagnostic, World Bank, Washington, DC.

Chapter 1
The Indus Basin Context

Key Points

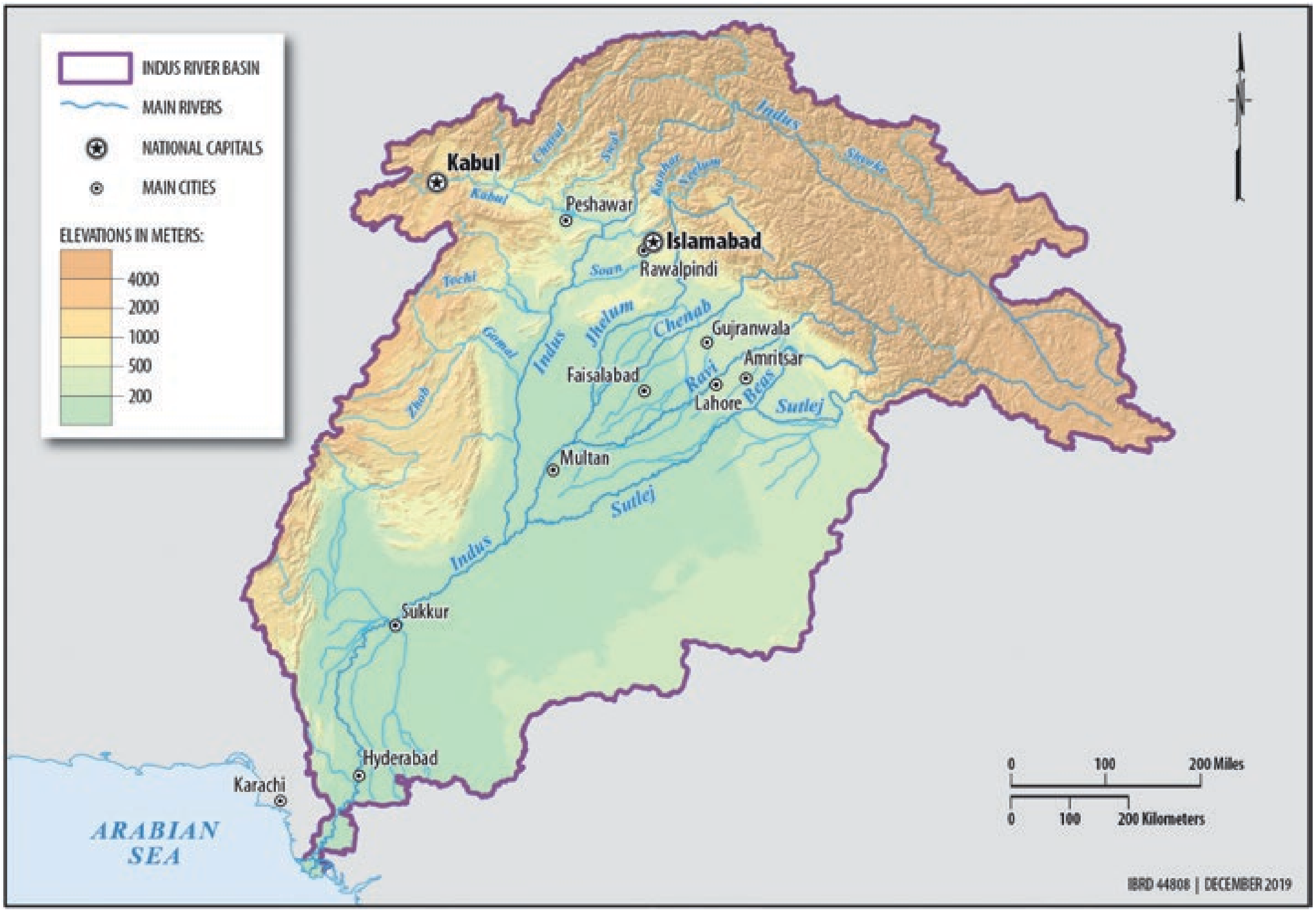
- The National Water Policy 2018 recognizes Pakistan's aquifers as important national resources that deserve protection from pollution and unsustainable abstractions. In keeping with these priorities, the objective of this report is to assist the federal and provincial governments of Pakistan to delineate an evidence-based pathway toward sustainable groundwater management in the Indus basin.
- The Indus basin covers about 65 percent of Pakistan's area, contains about 95 percent of Pakistan's water resources, and is of critical importance to Pakistan's economy.
- The Indus basin supports the largest contiguous irrigation network in the world, with groundwater as an important component of the water resource base.
- Groundwater in Pakistan lacks regulation and monitoring, a situation that has an effect on all water resources in the Indus basin because of their interconnected nature in this alluvial environment.
- Projected increases in water demand will put further stress on groundwater resources, and without institutional reform and capacity building, Pakistan will struggle to manage the hydrological, environmental, economic, and social risks associated with poor groundwater management.

Introduction

The Indus River is one of the longest rivers in Asia and is the national river of Pakistan. Its path of approximately 3,180 kilometers passes through China, India, Afghanistan, and Pakistan. The Indus basin watershed is home to 300 million people, of whom 183 million (61 percent)[1] live in Pakistan (Laghari et al. 2012). The basin's total area of 1.12 million square kilometers is distributed between Pakistan (520,000 square kilometers; 47 percent), India (440,000 square kilometers; 39 percent), China (88,000 square kilometers; 8 percent), and Afghanistan (72,000 square kilometers; 6 percent) (FAO 2012). The basin extends from the high mountains of the Hindu Kush Himalaya with an elevation of 5,000 meters to the Indus delta at sea level.

The Indus River originates in the Tibetan Plateau at Lake Manasarovar and passes through Ladakh, Gilgit-Baltistan, and the Hindu Kush range on to the Indus River plain and the Arabian Sea (map 1.1). This geography encompasses a variety of climatic regions, ranging from glacial areas, dry high mountains, and high rainfall mountainous areas to the semiarid Indus plain and the delta area. Accordingly, the Indus basin represents a unique ecosystem that ranges from cold mountains to hot and humid plains. Twelve

MAP 1.1. The Indus River Basin



large cities rely on water from the basin: Kabul (Afghanistan), Amritsar (India), and in Pakistan: Peshawar, Islamabad, Rawalpindi, Faisalabad, Gujranwala, Lahore, Multan, Sukkur, Hyderabad, and Karachi.

The total renewable water resource in Pakistan is estimated to be 229 billion cubic meters per year, or about 1,100 cubic meters per capita per year (Young et al. 2019), of which about 95 percent is from the Indus basin. This dependency on a single river system makes the water environment in Pakistan one of relatively high risk (Briscoe and Qamar 2005). On average, Pakistan is well endowed with water, and only 32 countries have more water available per capita. However, Pakistan's water productivity is in the bottom 5 percent in the world—about US$1.38 per cubic meter water withdrawn—and the productivity of water in agriculture in Pakistan is in the bottom 10 percent of world rankings, or about US$0.37 per cubic meter water withdrawn (Young et al. 2019).

Agriculture is the major user of water in Pakistan's Indus basin. The centrally managed expansive gravity-based irrigation systems in Pakistan are also vulnerable to seasonal fluctuations. Since the 1960s, this has helped motivate farmers to invest in developing private groundwater extraction facilities to improve reliability. Peak demand and peak supply overlap during the summer monsoon season, but irrigation supplies can fail to meet demand in the winter. This underscores the significance of groundwater to the agriculture sector, which accounts for 43 percent of the labor force and provides livelihood to about 64 percent of the rural population (Government of Pakistan 2018a).

The Indus basin is the heartland of irrigated agriculture in Pakistan, with the largest contiguous irrigation network in the world (FAO 2012). The annual surface water supply through this network is about 205 billion cubic meters with a canal command area of 16.2 million hectares and 125 billion cubic meters of annual canal diversions (Young et al. 2019).

Demand for water across the agriculture, domestic/municipal, industrial, and environment sectors is expected to rise between 2015 and 2025 in line with population growth (table 1.1). As demographics change, the relative proportion of water used by the agricultural sector is anticipated to decline. Nevertheless, the anticipated additional 12.8 billion cubic meters needed across these four sectors by 2025 means additional pressure on existing water resources.

Pakistan's 2010 per capita water availability of 1,500 cubic meters per year is expected to fall to 1,000 cubic meters per year by 2025 and to 900 cubic meters per year by 2050 as a result of population growth (Amir and Habib 2015). Based on 2018 data, this is already reported at about 1,100 cubic meters per year (Young et al. 2019). Agriculture will continue to dominate water demand. Of the water consumed by irrigation, current patterns indicate that 80 percent is used for irrigating wheat, sugarcane, rice, and cotton (Young et al. 2019).

Demand projections by Amir and Habib (2015) include assumptions for irrigation distribution efficiency and growth. In the absence of reform or major structural change to the economy, the total projected demand by 2047 will exceed the available water, highlighting the need to shift toward demand management (Young et al. 2019).

As agriculture is the major user of water in Pakistan's Indus basin, improvement in water productivity and the future sustainability of agriculture depends on both equitable water provisioning across sectors and adapting agricultural and cropping practices to suit changing water availability and competing demands.

TABLE 1.1. **Projected Demand for Water for Agriculture, Domestic, Industry, and Environment**

Major users of water	2015 (BCM)	2020 (BCM)	2025 (BCM)	Increase 2015–25 (BCM)	Increase 2015–25 (%)
Agriculture	136.9	141.9	146.8	9.9	7.2
Domestic/municipal	10.2	11.5	12.3	2.1	20.6
Industry	5.3	5.6	5.9	0.6	11.3
Environment	1.9	2.0	2.1	0.2	10.5

Source: Engro, reported in Amir and Habib 2015.
Note: BCM = billion cubic meters.

Three priorities were identified by Young et al. (2019) to help address this challenge:

- Improved monitoring of the resource and water accounting
- Strengthening institutional capacity to map water use and enforce pricing reforms
- Encouraging water savings through improved *abiana* rates (irrigation water charges) and 100 percent recovery of operation and maintenance costs

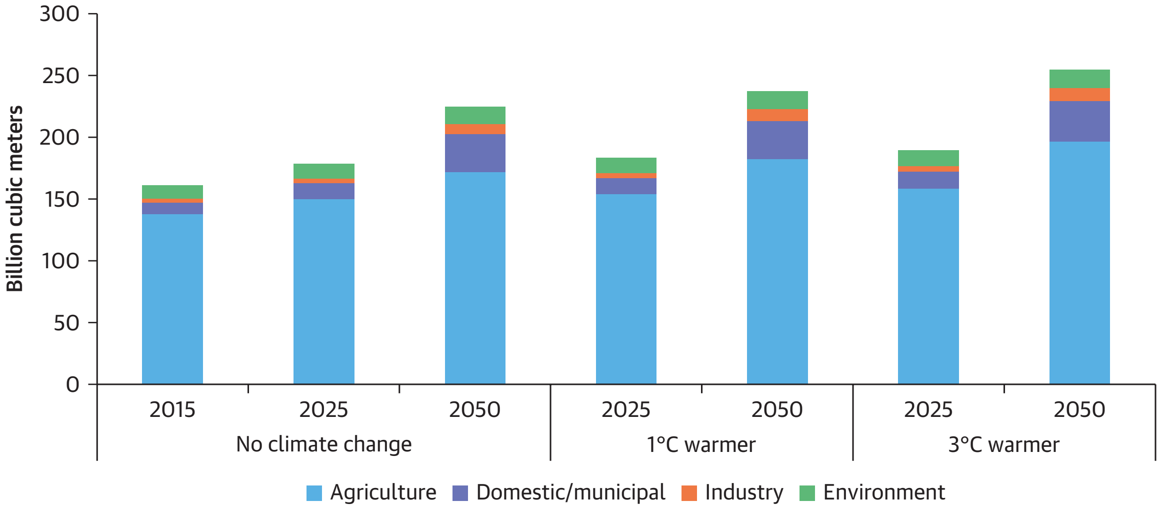
Understanding the Challenges

Water resources are critical to Pakistan's economy and for the health, well-being, and prosperity of its communities. However, the economic, social, and environmental outcomes Pakistan derives from its water are poor compared with countries with similar water endowment and sectoral allocations.

The three uses that dominate demand for water in Pakistan are agriculture, industry, and domestic (Amir and Habib 2015) (see figure 1.1). Groundwater is a constituent of all three. However, as 94 percent of available water is withdrawn for agriculture, the increasing use of groundwater for irrigation offers the greatest opportunity for groundwater development but also poses the greatest threat to sustainability. Pakistan is the fourth largest user of groundwater in the world[2] (Khalid and Qaisrani 2018), and groundwater meets about half of the country's irrigation needs (Briscoe and Qamar 2005).

The canal irrigation system in Pakistan was designed for a cropping intensity of approximately 67 percent across the system, but use of groundwater has substantially increased this, thereby improving farming livelihoods and food security. The alluvial aquifers of the Indus basin contain large quantities of fresh and marginal quality groundwater, and irrigators turn to groundwater use where and when surface water is (or becomes) unavailable, installing tube wells when the need arises.

FIGURE 1.1. **Pakistan Total Water Demand for 2015 and Projected for 2025 and 2050**



Source: Amir and Habib 2015.

A common occurrence in Punjab province is that the last one-third of canals do not get their share of surface water, so reliance on groundwater increases at the tail end of canals. In 1960, groundwater accounted for only 8 percent of farm water supplies in Punjab, a figure that had increased to 50 percent by 2010 (Bhutta 2016) and, in 2020, groundwater accounts for more than half of all irrigation requirements in the Punjab and up to 20 percent in Sindh. The greatest risk of groundwater depletion currently rests with irrigators at the tail ends of canals in the eastern doabs of Punjab and more generally within canal commands in Punjab and Sindh where surface water supply is unreliable.

Using groundwater is an attractive but expensive option, particularly for farmers near the end of irrigation canals. Increasing groundwater use can result in economic hardships for smallholder farmers who may not have the resources to deepen wells in response to declining groundwater levels.

Poor Water Quality

Salinity and waterlogging are also significant issues in Pakistan's Indus basin. Irrigation is estimated to add approximately 1 ton of salt per irrigated hectare per year to the shallow groundwater of the Indus basin (Ali 2018; Qureshi 2011). Although a proportion of this comes from surface water, deeper groundwater naturally contains more salts, and its use in irrigation serves to bring more salt to the surface. Much of the deeper groundwater in the Indus basin is saline, and high rates of extraction from freshwater lenses risks upconing of underlying saline groundwater—saline intrusion from adjacent groundwater bodies and from the sea. The cumulative effect of this salt load across the irrigated 16 million hectares of the Indus basin requires careful management of the water and salt balance to ensure sustainability of irrigated agriculture (Ali 2018).

Although most prevalent in Sindh, waterlogging and groundwater salinization occur across the Indus basin. These issues are exacerbated by canal seepage, poor drainage, and excessive irrigation. On the other hand, canal seepage forms freshwater lenses that overlie native saline groundwater and provide essential drinking water supplies to communities in these areas (Ensink et al. 2002; Jensen et al. 1998).

In Pakistan, most of the population obtains drinking water from groundwater (Chandio, Abdullah, and Tahir 1999; Raza et al. 2017), and many millions of people are exposed to unsafe drinking water. Poor-quality drinking water prevails in most of the cities and towns in the Indus basin in Pakistan (Kahlown, Tahir, and Rasheed 2007). Khwaja and Aslam (2018) report earlier work by the Pakistan Council of Research in Water Resources (PCRWR) (Tahir, Rasheed, and Imran 2010) indicating that water-linked diseases in Pakistan cause national income losses of PRs 25 billion to 28 billion annually, approximately 0.6 to 1.44 percent of the country's gross domestic product (GDP). Financial losses resulting from the effects of saline irrigation water on agricultural production are additional to this.

Poor waste management and inadequately treated effluents introduce microbiological contamination to groundwater, and dissolved ions, such as nitrate and ammonium, from agricultural activities are entering water supplies. Industrial processes are responsible for pollutants, such as cadmium, lead, and arsenic, whereas naturally occurring geogenic contaminants, such as fluoride and arsenic, are a serious problem in some areas.

Declining water quality is of major concern as groundwater use increases, risking high economic costs in terms of health hazards and land degradation. Women and children are disproportionately affected by poor and declining groundwater quality, and effects include health risks, loss of income, reduced productivity, increased costs, and additional time spent fetching water from greater distances.

Data Challenges

Despite the rapid expansion of groundwater irrigation in Pakistan over the past 30 years, systematic long-term monitoring and archiving of groundwater data are largely absent. The potential for improving water management is undermined by scant groundwater information for the Indus basin (Young et al. 2019).

Limited long-term groundwater monitoring has been undertaken by federal agencies in Pakistan from the mid-1970s to 2015, and more recently (2008 to 2014) by the Punjab Irrigation Department in the eastern doabs of Punjab. In Sindh, there is virtually no groundwater monitoring.

Available groundwater data are often of poor quality (imprecise date or measurement) and of doubtful authenticity (estimated rather than measured). Transport in the field, staff capacity, equipment problems, and similar issues complicate groundwater data collection. Poor storage and retrieval systems for such groundwater data as does exist further confound assessment and management of groundwater. Unreliable data (an “unknown unknown”) is a greater threat to water management than no data as they support a false understanding of reality—arguably worse than complete ignorance.

Research projects conducted by universities, consultancies, and other organizations include the collection of groundwater data, but these tend to be limited in time and space, are largely held by individuals, and are not easily accessible. Unmonitored increases in groundwater use coupled with unmonitored changes in groundwater resource conditions represent a significant risk to Pakistan’s ability to manage groundwater resources.

Climate Change

Pakistan’s Indus basin is the base resource on which Pakistan’s economy is founded, and the water-stressed basin already suffers water shortages in its middle and downstream segments. Because of population increase, some authors indicate the annual water availability per capita has already dropped below the water scarcity threshold level of 1,000 cubic meters (IMF 2015; UNDP 2006) and FAO AQUASTAT data suggest that availability is less than half of this in areas such as the Pothwar region.

Climate change, including the projected retreat of glaciers that supply the Indus River, is a threat to water security (UNDP-Pakistan, 2017) and the sustainability of the water services in the Indus basin (Hussain and Mumtaz 2014). Floods and droughts risk the life and livelihood of millions of people, and migration driven by water stress is also increasing (Ali 2013). Although the real impact is seen in cumulative long-term trends, the destructive and disruptive effect of changes to the Indus River is also evident in single extreme events. For example, the 2010 floods caused direct losses of more than US$10 billion and 1,600 deaths and affected 38,600 square kilometers (Ali 2013). Increasing spatial and temporal water variability further heightens water shortages and has the potential to cause conflict (Wescoat 2009).

Future changes to precipitation, crop water demand, snowpack and glacier cover, evapotranspiration, and other parameters linked to groundwater dynamics are difficult to predict, but changes are likely to put additional pressure on Pakistan's water resources (Yu et al. 2013).

Although climate change impacts may be unpredictable, demographic trends are not. Because population trends will exert a measurable effect on groundwater resources, they can be provisioned with foresight.

The Impact of the Indus Basin Irrigation System

The advent of large-scale irrigation in the 19th century provided the platform for the development of the modern economy of Pakistan. Vast quantities of water were used to flood-irrigate desert lands where the underlying groundwater was relatively deep and saline.

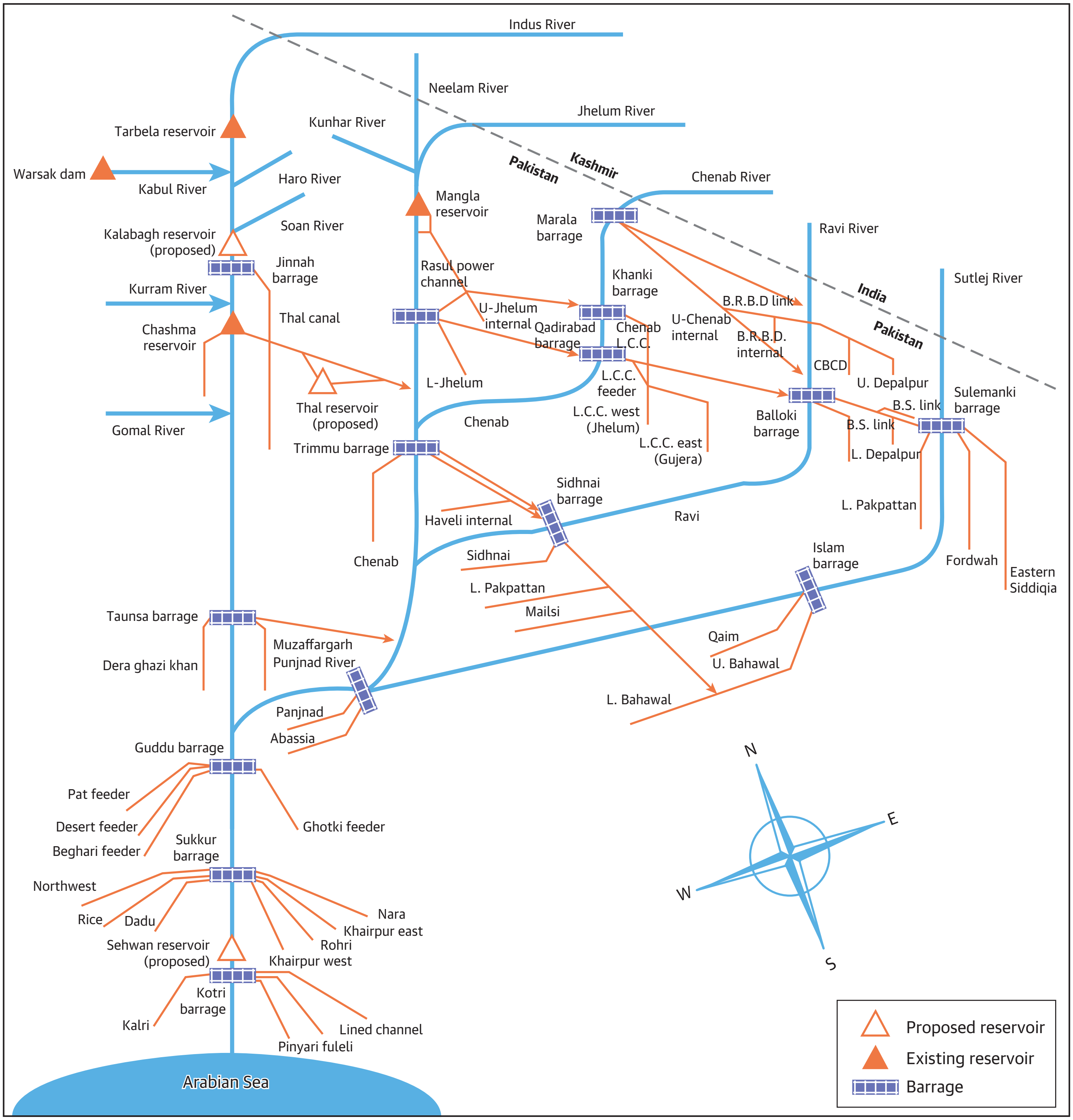
The Indus basin's irrigation distribution infrastructure (figure 1.2) comprises Mangla reservoir (9.12 cubic kilometers capacity), Tarbela reservoir (11.96 cubic kilometers capacity as original and 7.9 cubic kilometers current), 19 barrages, 14 link canals, 45 irrigation canals (totaling about 60,800 kilometers in length), and 1.6 million kilometers of watercourses. About 36 percent of the area is irrigated from Mangla reservoir and 64 percent from Tarbela reservoir (WCD 2000).

The first major modern canal to be constructed was the Upper Bari Doab Canal in the easternmost doab in the Indus basin in Pakistan. The water rights of canal commands within each province are based on the design water allowance. Historical use and canal water allocations have been reviewed periodically on a provincial basis for establishing water rights on Indus River flows among the four provinces. Water allowances and canal water distributions allow for increasing crop water requirements in a southerly direction (higher water allowance in Sindh as compared with Punjab). However, within Punjab, the canal water supplies ignore variation in irrigation demand because of increasing evapotranspiration and decreasing rainfall across the canal commands from north to south. The subsequent imbalance in canal water delivery has resulted in farmers turning to groundwater as an alternative water source in Bari doab and its consequent depletion (Basharat and Tariq 2014), whereas in other canal commands, in Sindh particularly, it has resulted in waterlogging.

The development of the initial canal irrigation system between 1870 and 1930 led to a rise in the water table, reaching 3.0 to 4.5 meters below ground level by 1940 in some areas, and a survey conducted in 1953 to 1954 (the Colombo Plan Survey) reported that rising water tables had caused waterlogging across an area of more than 5 million hectares (Mohammad and Beringer 1963).

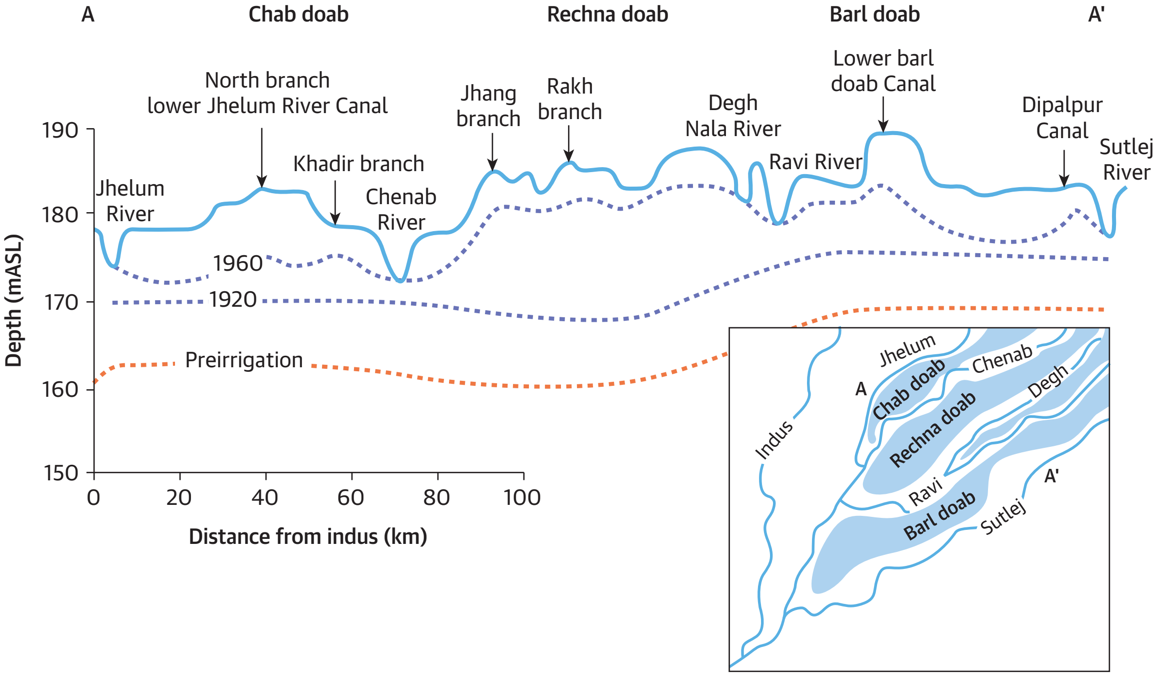
The Indus Waters Treaty of 1960 resulted in a gradual reduction in flows for the three eastern rivers as they enter Pakistan (Young et al. 2019). The transfer of water from the western rivers (Chenab, Indus, and Jhelum) to the eastern rivers (Beas, Ravi, and Sutlej) via link canals originated in the Indus Waters Treaty, with control of the waters of the three eastern rivers vested in India. As a result, Pakistan transfers surface water from the western rivers of the Indus basin to support flow in the eastern rivers once they have entered Pakistan. This massive transfer of water via linked canals, and the expansion of the canal network and of irrigated areas, contributed to the leakage to the groundwater system and to rising groundwater levels (figure 1.3) and the associated problems of waterlogging and secondary salinity (Mohammad and Beringer 1963).

FIGURE 1.2. **Schematic Diagram of Indus Basin Irrigation System**



Source: Young et al. 2019.

FIGURE 1.3. Historical Rise in the Water Table in Punjab



Source: Yu et al. 2013.
Note: km = kilometer; mASL = meters above sea level.

Groundwater use in Pakistan started to accelerate from the 1960s when public tube wells were installed to control rising water tables in waterlogged areas (Bhutta and Smedema 2007), and to assist in addressing this problem, private tube wells were promoted for agricultural production in areas with good-quality groundwater. Groundwater use was further encouraged by subsidizing electricity for private groundwater pumping. This led to rapid growth as more farmers installed private tube wells to meet irrigation shortfalls that the surface system was unable to supply—and from a resource that is more widely distributed and available "on demand."

In the 1980s, a 227 percent increase in electric tube wells led the government to remove the subsidy on electricity for tube wells and introduce a flat-rate tariff. The availability of cheap diesel pumps and the increased operational cost of electric tube wells caused many farmers to switch to diesel engines for tube well irrigation.

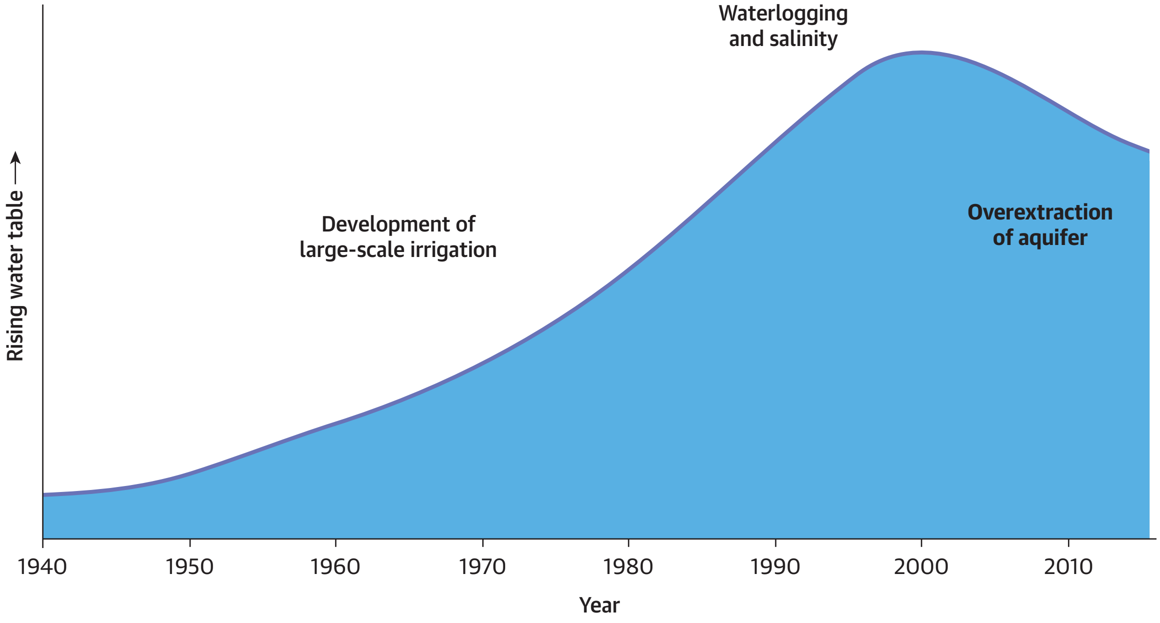
Between 1965 and 2002 a fivefold increase in groundwater extraction was observed (Qureshi et al. 2010), with burgeoning signs of groundwater depletion.

Figure 1.4 depicts the trends in groundwater levels in the Punjab since the 1940s and reflects the widespread view that groundwater depletion there is unsustainable. Although this is true for large areas of the province, particularly in the eastern part, overexploitation of groundwater resources is not occurring over the entire province and can be quite localized. Accurate assessment of the extent of the depletion is limited because data on groundwater extraction, levels, and quality are scarce or unreliable. The impact is understood locally through its effects on users. For instance, in Lower Bari doab in Sahiwal and Khanewal districts, a gradual decline in water levels is increasing pumping costs for farmers and reducing water quality as freshwater lenses are depleted (Basharat and Tariq 2014). Similarly, it is understood that water tables are shallower at the heads of the canals and deeper (yet in higher demand) at the tail end of canals. Because of the heterogeneous nature of the aquifer, changes to groundwater conditions are not uniform and data at a greater spatial and temporal resolution than are currently available are needed.

Although more muted than in Punjab, the growth in tube wells is also evident in Sindh, where 100,000 are owned and operated by farmers (compared with more than 1 million in Punjab). Waterlogging is still widespread in Sindh, and tube wells in this province are restricted to freshwater zones within the irrigated areas, which compose about 20 percent of the irrigated area. In Sindh, freshwater lenses overlie saline groundwater, and highly saline groundwater is present in areas immediately adjacent to the freshwater zones. This context means groundwater pumping of the freshwater is risky and needs careful monitoring and management.

Young et al. (2019) report that current groundwater withdrawals in Pakistan's Indus basin exceed the rate of renewal by about 1 billion cubic meter per year. Although evident only in parts of the basin, the rate of decline in some areas is raising social, economic, and environmental concerns. Access to shallow

FIGURE 1.4. Trend in Groundwater Use in Pakistan



Source: After Watoo 2015.

groundwater is vital for sparse vegetation cover and for crops, such as date palms in arid and semiarid plains. The environmental concerns include increased risks of salinity from upconing and lateral intrusion into freshwater aquifers (see box 1.1); seawater intrusion in the coastal region of the Indus basin; and long-term risks, such as drying up of lakes and wetlands, loss of vegetation, and land subsidence.

The dramatic increase in groundwater use now represents a policy challenge for the government of Pakistan. Although intensive groundwater use has relieved the symptoms of waterlogging and salinity in parts of Punjab and contributed to increased cropping intensities, these benefits are balanced by problems associated with the uncontrolled use of groundwater for irrigation, which has led to the depletion of groundwater resources in some areas and ongoing waterlogging and salinity issues in others (Basharat and Tariq 2014). Farmers at the tail end of canals who do not receive an equitable share of surface water use groundwater for irrigation, often of poor quality, which exacerbates salinity problems and damages agricultural land. Recent developments in solar pumping technology may foster a further increase in groundwater usage if there is no

BOX 1.1. Groundwater Salinity Risks

Inland Wells

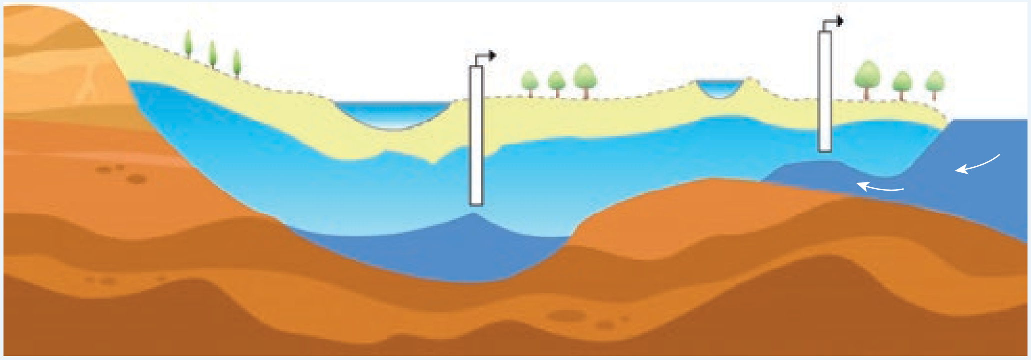
Groundwater at depth in the Indus basin is naturally saline. Unregulated groundwater pumping often results in upconing, which results in increased salinity of groundwater that is being pumped.

Coastal Wells

Pumping wells in coastal aquifers are particularly prone to upconing and seawater intrusion, as shown in the figure B1.1.1. Wells close to the coast tap the freshwater lens, which overlies seawater.

Pumping from coastal wells, or from deep wells where the salinity of groundwater increases with depth, requires careful management of pumping rates for sustainable water supply.

FIGURE B1.1.1. Salinity Risk Enhanced by Pumping



control on the pumping capacity of such installations (Gupta 2019). These challenges are linked to the expectation that irrigation, supported by a system designed for a cropping intensity of 67 percent, can, with the addition of groundwater, support cropping intensities of more than 150 percent.

Briscoe and Qamar (2005) estimated the groundwater economy in agriculture as equal to PRs200 billion (US$3.35 billion) annually, or roughly 5 percent of Pakistan's GDP in 2005. The number of tube wells has more than doubled since then, and the size of the groundwater economy in agriculture is likely to have increased significantly.

Although of tremendous benefit, access to groundwater has not been a panacea for Pakistan's farmers. Crop yields in Pakistani Punjab remain consistently lower than in Indian Punjab, and Pakistan's water productivity in agriculture in 2015 was only US$0.37 per cubic meter of water withdrawn, among the lowest in South Asia (Young et al. 2019). The increase in cropping intensity, necessary to improve food security, means that the use of both surface water and groundwater for irrigation needs to be efficient and sustainable, yet the need for judicious use of water for irrigation has largely been bypassed in favor of expanding the canal network or seeking out new sources of water.

The Road Ahead: Improving Understanding of Groundwater in the Indus Basin

Groundwater is foundational to Pakistan's growing economy. Demand and use continues to increase in almost all of Pakistan's water use sectors, so the condition of groundwater is pivotal to Pakistan's future health, agriculture, and industry.

Water resources in the Indus basin are among the most highly committed water resources in the world (Briscoe and Qamar 2005). Several studies have highlighted the growing water crisis in Pakistan (Condon et al. 2014; Kirby and Ahmad 2014; Mustafa, Akhter, and Nasrallah 2013). It is recognized that Pakistan is becoming more water stressed because of high population growth and that this may worsen and develop into an outright water scarcity (Briscoe and Qamar 2005). Water security in the country is undermined by poor water resource management (Young et al. 2019), and a lack of groundwater information and weak institutional arrangements threaten this key resource.

The National Water Policy 2018 (Government of Pakistan, 2018b) recognizes Pakistan's aquifers as important national resources that deserve protection from pollution and unsustainable abstractions. In keeping with these priorities, the objective of this report is to assist the federal and provincial governments of Pakistan to delineate an evidence-based pathway toward sustainable groundwater management in the Indus basin. Chapter 2 identifies the uses of groundwater in the Indus basin, and chapter 3 covers the natural characteristics, capacity, and limitations of the groundwater aquifer and the pressures being exerted on it. Chapter 4 outlines the institutional capacity for managing this resource, and chapter 5 identifies local, regional, and international examples for managing groundwater challenges similar to those encountered in the Indus basin. Chapter 6 contains report conclusions, recommendations for tackling large and small challenges in Pakistan's Indus basin, and guidance on implementation.

Notes

1. The projected population in 2018.
2. After India, the United States, and China (Margat and van der Gun 2013).

References

Ali, A. 2013. *Indus Basin Floods: Mechanisms, Impacts, and Management*. The Philippines: Asian Development Bank. http://hdl.handle.net/11540/810.

——. 2018. "Improving Salinity and Agricultural Water Management in the Indus Basin, Pakistan: Issues, Management and Opportunities. A Synthesis from Desktop Literature Review." ACIAR-Financed Short-Time Research Activity for Preparing the Project on Management of Salinity and Agricultural Water Management in the Pakistan's Indus Basin.

Amir, P., and Z. Habib. 2015. "Estimating the Impacts of Climate Change on Sectoral Water Demand in Pakistan." ACT Report, Action on Climate Today, Nottinghamshire, U.K. Accessed March 2019. https://cyphynets.lums.edu.pk/images/Readings_concluding.pdf.

Basharat, M., and A. U. R. Tariq. 2014. "Command-Scale Integrated Water Management in Response to Spatial Climate Variability in Lower Bari Doab Canal Irrigation System." *Water Policy* 16: 374–96.

Bhutta, M. N. 2016. "Groundwater Development and Management in Pakistan." Report prepared for Pakistan Engineering Council.

Bhutta, M. N., and L. K. Smedema. 2007. "One Hundred Years of Waterlogging and Salinity Control in the Indus Valley, Pakistan: A Historical Review." *Irrigation and Drainage* 56: S81–S90. doi:10.1002/ird.333

Briscoe, J., and U. Qamar. 2005. "Pakistan's Water Economy: Running Dry." Water P-Notes 17, World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/11746.

Chandio, B. A., M. Abdullah, and M. A. Tahir. 1999. "Drinking Water Quality and Standardization in Pakistan" in Proceedings of the National Workshop on Quality of Drinking Water, Islamabad, March 7, 1998. https://www.ircwash.org/sites/default/files/242-15920.pdf

Condon, M., D. Kriens, A. Lohani, and E. Sattar. 2014. "Challenge and Response in the Indus Basin." *Water Policy* 16 (S1): 58–86.

Ensink, J. H. J., M. R. Aslam, F. Konradsen, P. K. Jensen, and W. van der Hoek. 2002. "Linkages between Irrigation and Drinking Water in Pakistan." IWMI Working Paper 46, International Water Management Institute, Colombo, Sri Lanka.

FAO (Food and Agriculture Organisation). 2012. Irrigation in Southern and Eastern Asia in figures. AQUASTAT Survey - 2011 FAO WATER REPORTS. Editor K. FRENKEN, FAO Land and Water Division. 37. Rome. http://www.fao.org/3/i2809e/i2809e.pdf

Government of Pakistan. 2018a. *Pakistan Economic Survey 2017–18.* Economic Adviser's Wing, Finance Division, Government of Pakistan, Islamabad. Accessed April 9, 2019. http://www.finance.gov.pk/survey/chapters_18/Economic_Survey_2017_18.pdf.

——. 2018b. *National Water Policy 2018.* Ministry of Water Resources, Government of Pakistan, Islamabad. Accessed April 9, 2019. https://mowr.gov.pk/wp-content/uploads/2018/06/National-Water-policy-2018-.pdf

Gupta, E. 2019. "The Impact of Solar Water Pumps on Energy-Water-Food Nexus: Evidence from Rajasthan, India." *Energy Policy* 129: 598–609.

Hussain, M., and S. Mumtaz. 2014. "Climate Change and Managing Water Crisis: Pakistan's Perspective." *Reviews on Environmental Health* 29 (1-2): 71–77. Accessed November 13, 2019. doi:10.1515/reveh-2014-020.

IMF (International Monetary Fund). 2015. "Issues in Managing Water Challenges and Policy Instruments: Regional Perspectives and Case Studies." Technical Companion Note to SDN/15/11, IMF.

Jensen, P. K., W. van der Hoek, F. Konradsen, and W. A. Jehangir. 1998. "Domestic Use of Irrigation Water in Punjab" IN: Pickford, J. (ed). Sanitation and water for all: Proceedings of the 24th WEDC International Conference, Islamabad, Pakistan, 31 August-4 September 1998, pp.297-299.

Khalid, I. S., and A. Qaisrani. 2018. "Groundwater Management: Pathways for Cooperation in South Asia." Issue brief. Sustainable Development Policy Institute. Islamabad. https://think-asia.org/bitstream/handle/11540/8965/Groundwater-Management-Pathways-for-Cooperation-in-South-Asia(PB-64).pdf?sequence=1

Kahlown, M. A., M. A. Tahir, and H. Rasheed. 2007. Water Quality Status of Pakistan (5th Technical Report 2005-2006). Islamabad: Pakistan Council of Research in Water Resources. http://www.pcrwr.gov.pk/Publications/Water%20Quality%20Reports/Water%20Quality%20Monitoring%20Report%202005-06.pdf

Khwaja, M., and A. Aslam. 2018. *Comparative Assessment of Pakistan National Drinking Water Quality Standards with Selected Asian Countries and World Health Organization.* Islamabad. Sustainable Development Policy Institute. Accessed February 24, 2020. www.jstor.org/stable/resrep17217.

Kirby, M., and M. Ahmad. 2014. *Water Resources Management in Developing Countries: The Role of Hydrology - Economic Modelling.* Australia: CSIRO Land and Water Flagship.

Laghari, A. N., Vanham, D., and Rauch, W. 2012. The Indus basin in the framework of current and future water resources management, Hydrology and Earth Systems Sciences, 16, 1063-1083, https://doi.org/10.5194/hess-16-1063-2012.

Margat, J., and J. van der Gun. 2013. Groundwater Around the World: A Geographic Synopsis. Hove: Taylor & Francis Ltd.

Mohammad, G., and C. Beringer. 1963. "Waterlogging and Salinity in West Pakistan: An Analysis of the Revelle Report." *The Pakistan Development Review* 3 (2): 250–78.

Mustafa, D., M. Akhter, and N. Nasrallah. 2013. *Understanding Pakistan's Water-Security Nexus.* Washington, DC: United States Institute of Peace.

Qureshi, A.S., McCornick, P.G., Sarwar, A. et al. Challenges and Prospects of Sustainable Groundwater Management in the Indus Basin, Pakistan. 2010. Water Resources Management 24 (2010): 1551-1569. https://doi.org/10.1007/s11269-009-9513-3

Qureshi, Asad Sarwar. 2011. "Water Management in the Indus Basin in Pakistan: Challenges and Opportunities." *Mountain Research and Development* 31(3): 252–60.

Raza, Maimoona, Fida Hussain, Jin-Yong Lee, Muhammad Shakoor, and Kideok Kwon. 2017. "Groundwater Status in Pakistan: A Review of Contamination, Health Risks, and Potential Needs." *Critical Reviews in Environmental Science and Technology* 47 (18): 1713–62.

Tahir, M. A., H. Rasheed, and S. Imran. 2010. *Water Quality Status in Rural Areas of Pakistan.* Islamabad. Pakistan Council of Research in Water Resources.

UNDP (United Nations Development Programme). 2006. "Beyond Scarcity: Power, Poverty and the Global Water Crisis." Human Development Report 2006, UNDP, New York.

UNDP-Pakistan. 2017. The Vulnerability of Pakistan's Water Sector to the Impacts of Climate Change: Identification of gaps and recommendations for action. https://www.pk.undp.org/content/pakistan/en/home/library/environment_energy/PakistanWaterSectorReport.html

Watoo, M. A. "The Economics of Groundwater Irrigation in the Indus Basin, Pakistan: Tube-well Adoption, Technical and Irrigation Efficiency and Optimal Allocation." PhD thesis, University of Western Australia, School of Agricultural and Resource Economics, 2015.

WCD (World Commission on Dams). 2000. *Dams and Development: A New Framework for Decision-Making.* London: Earthscan Publications Ltd. https://www.internationalrivers.org/sites/default/files/attached-files/world_commission_on_dams_final_report.pdf.

Wescoat, J. L. 2009. "Water Shortages and Water-Conserving Urban Design in Pakistan." In *Running on Empty Pakistan's Water Crises,* edited by M. Kugelman and R. M. Hathaway. Washington, DC: Woodrow Wilson International Center for Scholars, pp 129 - 152.

Young, W. J., A. Anwar, T. Bhatti, E. Borgomeo, S. Davies, W. R. Garthwaite, E. M. Gilmont, C. Leb, L. Lytton, I. Makin, and B. Saeed. 2019. "Pakistan: Getting More from Water." Water Security Diagnostic, World Bank, Washington, DC.http://documents1.worldbank.org/curated/en/251191548275645649/pdf/133964-WP-PUBLIC-ADD-SERIES-22-1-2019-18-56-25-W.pdf

Yu, Winston, Yi-Chen Yang, Andre Savitsky, Donald Alford, Casey Brown, James Wescoat, Dario Debowicz, and Sherman Robinson. 2013. *The Indus Basin of Pakistan: The Impacts of Climate Risks on Water and Agriculture.* Washington, DC: World Bank. doi:10.1596/978-0-8213-9874-6.

Chapter 2
Groundwater Uses in Pakistan's Indus Basin

Key Points

- Groundwater is an increasingly important foundation of Pakistan's growing economy and is pivotal to Pakistan's future health, agriculture, and industry. Its use is increasing in each of these sectors.
- More than 70 percent of Pakistan's drinking water is from groundwater. Most major cities in Pakistan depend mainly on groundwater for domestic supplies. Domestic water demand will nearly double by 2050.
- Agriculture uses about 90 percent of the total freshwater resource in Pakistan, but productivity per unit of water is low, and waterlogging and soil salinity are growing problems. More than half of irrigation requirements in Punjab, and up to 20 percent in Sindh, are supplied by groundwater.
- Reallocation from low- to high-priority sectors and between surface and groundwater uses will occur as a function of demographic changes such as population growth and urbanization. A resulting increasing emphasis on domestic and industrial water supplies at the expense of agricultural allocations is likely.

Introduction

Population growth, urbanization, and changes in lifestyle and economic development are driving water use and demand for food and fiber in the Indus basin in Pakistan. Although agricultural water use dominates, urbanization and changes in lifestyle are increasing household water demand, and industrial water demand is rising with economic growth. Groundwater contributes a major proportion of the total water supply to every sector in Pakistan.

According to the 2017 census, Pakistan's population increased from 132 million in 1998 to 208 million in 2017, an annual growth rate of 2.4 percent or a near 57 percent increase over those 19 years (Government of Pakistan 2018). In 2017, about 36 percent of the population lived in urban areas and 64 percent in rural areas (table 2.1). The growth rate in urban areas was 2.7 percent compared to 2.2 percent in rural areas, with the higher urban growth rate attributable to urban migration. In Sindh, the urban population is highest at 52 percent, followed by Punjab at 37 percent, Balochistan at 28 percent, and Khyber Pakhtunkhwa at 19 percent.

National water use in Pakistan gradually increased from 153.4 billion cubic meters in 1975 to 183.5 billion cubic meters in 2008 (FAO 2012), an overall increase of about 20 percent in 33 years. In the same period,

TABLE 2.1. Pakistan's Population as per Census 2017 and Projections to 2050

	Population census, 2017[a]			Population as a percentage of total population, 2017[b]		Projected population, 2050 (urban 52%, rural 48%[c])		
Description	**Urban**	**Rural**	**Total**	**Urban**	**Rural**	**Urban**	**Rural**	**Total**
Pakistan	75,584,989	132,189,531	207,774,520	36	64	175,766,862	162,246,334	338,013,196
Balochistan	3,400,876	8,943,532	12,344,408	28	72	10,442,752	9,639,464	20,082,216
FATA	141,899	4,859,778	5,001,677	3	97	4,231,169	3,905,694	8,136,863
KP	5,729,634	24,793,737	30,523,371	19	81	25,821,246	23,834,997	49,656,243
Punjab	40,387,298	69,625,144	110,012,442	37	63	93,065,029	85,906,180	178,971,209
Sindh	24,910,458	22,975,593	47,886,051	52	48	40,509,206	37,393,114	77,902,320
Islamabad	1,014,825	991,747	2,006,572	51	49	1,697,460	1,566,886	3,264,346

Note: FATA = Federally Administered Tribal Areas; KP = Khyber Pakhtunkhwa.

a. Based on census data for Pakistan.

b. Population Division, Population Prospects 2019 (database), United Nations, https://population.un.org/wpp/Download/Probabilistic/Population/.

c. Population Division, World Urbanization Prospects 2018 (database), United Nations (accessed December 2, 2019), https://population.un.org/wup/Country-Profiles/.

the population increase was 156 percent.[1] The rate of increase in population was many times higher than the rate of increase in water use (and availability) and explains the increasing water scarcity trend over the past three decades.

Groundwater Use in Agriculture

Agriculture is by far the largest user of groundwater in Pakistan. Although irrigation in the Indus basin has taken place for centuries (Alam, Sahota, and Jeffrey 2007), a surge of development occurred between the late 1800s and the 1940s (FAO 2012). Following the signing of the Indus Waters Treaty in 1960 and the subsequent construction of new dams, the Indus basin irrigation system (IBIS) was further developed in the 1960s and 1970s and supported the expansion of irrigated agriculture over an area of 16 million hectares in Pakistan's Indus basin. Seepage from the extensive network of irrigation canals spanning 56,000 kilometers in the IBIS contributed to the development of shallow groundwater and caused serious waterlogging and salinity problems in many areas. Even before this later expansion, the severity of the problem in Punjab was identified by the early 1950s (Mohammad and Beringer 1963).

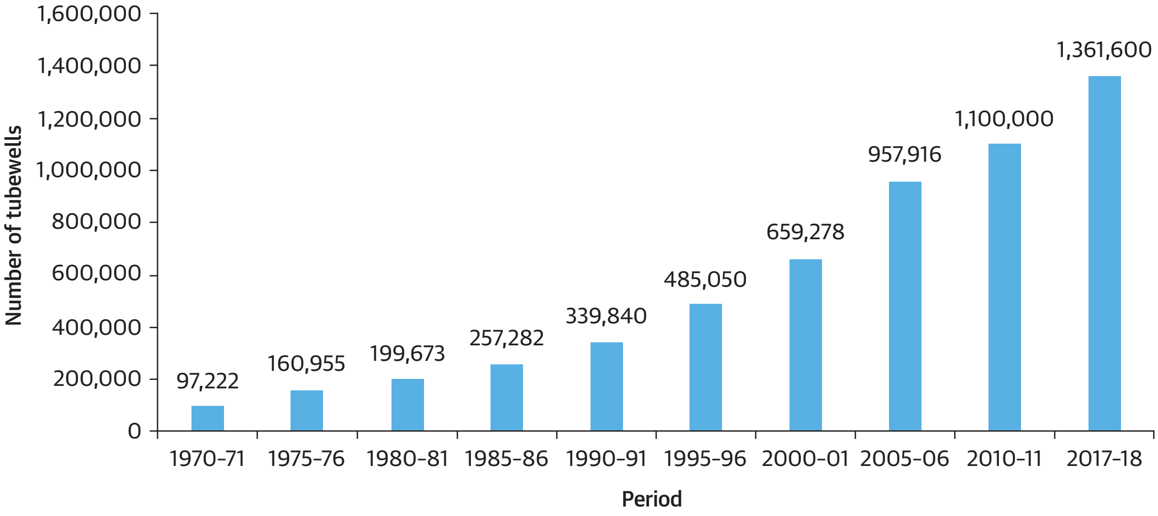
Attempts to manage waterlogging and salinity contributed to the widespread use of groundwater for irrigated agriculture, starting in the 1960s with the launch of the Salinity Control and Reclamation Project (SCARP). Thousands of large-capacity tube wells were installed to control the groundwater table and supplement irrigation supplies. The handover of SCARP tube wells to private farmers and the provision of subsidies for private groundwater pumping led to rapid uptake with thousands of farmer-owned tube wells being installed, particularly during the prolonged drought and surface water shortage of 1996–2001. These private tube wells had a capacity of about 1,200 to 2,400 cubic meters per day (0.5 to 1 cubic foot per second). What started as a planned conjunctive management strategy became unplanned conjunctive use[2] with individual farmers able to make decisions about water sources at the farm level.

Between 1976 and 2012, the contribution of groundwater to irrigated agriculture doubled from 31.6 billion cubic 59.95 billion cubic meters (Friends of Democratic Pakistan, 2012). With the restraints on large-scale surface water development since 1976, agricultural expansion and intensification in the country has been driven to a very large extent by the development of over 1,000,000 private tube wells, powered either by electricity (15%) or by diesel (85%) (Friends of Democratic Pakistan, 2012) and the number of tube wells increased from a few thousand in the early 1970s to nearly 1.4 million by 2018 (see figure 2.1). The increase in electric tube wells has slowed due to the rise in the electricity tariff and to power outages

Most of the increase in groundwater withdrawals for irrigation has occurred in Punjab, and about 70 percent of the private tube wells are in the canal command areas, whereas the rest provide solely groundwater-based irrigation (Jehangir, Turral, and Khan 2003).

Although agriculture uses more than 90 percent of the total freshwater resource in Pakistan (ACE, EGC, and SMEC 2011), many areas face a shortage of irrigation water during part of the year. For example, during Rabi season in 2017-18, the shortfall in irrigation water compared to the previous year was 20 percent in Punjab, 19 percent in Sindh, and 10 percent in Khyber Pakhtunkhwa (Government of Pakistan 2018). The shortage of irrigation water at critical crop growth stages significantly reduces crop yield and overall agricultural production and discourages farmers from investing. The installation of private tube wells in 70 percent of the canal command areas has helped farmers to supplement irrigation by using groundwater at critical crop stages when adequate canal water is not available. This conjunctive use of surface and groundwater has helped farmers stabilize

FIGURE 2.1. Increase in Number of Tube Wells in the Indus Basin

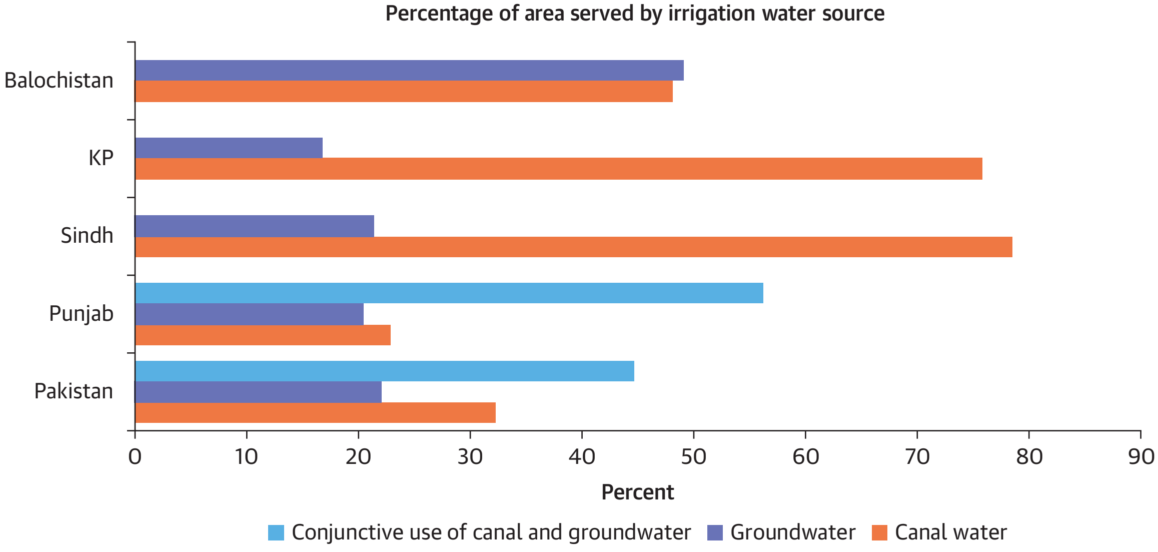


Source: Data from Government of Pakistan 2018.

crop yields, improve agricultural production, and reduce the risk of crop failure. Because of disparity of water distribution along the canals, the farmers' dependence on groundwater has increased from 65 percent at the head of the canals to 90 percent in the tail areas, which suggests groundwater as an integral part of the irrigation system rather than as a supplementary source of water (Qureshi 2015). Pakistan statistics for 2017 show that of the total irrigated area of 18.21 million hectares (of which the majority is in the Indus basin), 5.88 million hectares (32.2 percent) is irrigated by canal water, 4.02 million hectares (22.2 percent) is served exclusively by groundwater, and 7.85 million hectares (43.1 percent) is served by conjunctive use of canal and groundwater. The balance of 0.46 million hectares (2.5 percent) is served by other sources (Government of Pakistan 2018). Figure 2.2 shows the percentage of irrigated area served by different water sources, including canal water, groundwater, and the conjunctive uses of surface and groundwater.

About 79 percent of the area of Punjab has groundwater suitable for irrigation (Mott MacDonald and Partners 1990), and groundwater accounts for more than 50 percent of the total irrigation water used. The groundwater irrigated area in Punjab expanded from 8.65 million hectares in 1960 to 14.7 million hectares in 2014—an almost 70 percent increase (Government of Pakistan 2014). As of 2017, conjunctive use of surface and groundwater was practiced in more than 56 percent of the irrigated area of Punjab. About 23 percent of this irrigated area depends exclusively on surface water, and 20 percent relies solely on groundwater (figure 2.2). The remaining 1 percent is served by other water sources, such as tank irrigation. Although not shown in figure 2.2, other sources (Mangan et al. 2016) report a high percentage of Sindh farmers adopting conjunctive use. Farmers opt for more reliable groundwater particularly when canal water supply is inadequate. The increasing use of groundwater in agriculture also incentivizes farmers to use high-efficiency irrigation

FIGURE 2.2. Percentage of Irrigated Area Served by Different Sources of Water



Source: Data from Government of Pakistan 2017.
Note: KP = Khyber Pakhtunkhwa.

systems. The conjunctive use of surface water and groundwater in agriculture improves reliability, water productivity, and farm profitability while also allowing increased cropping intensity.

Groundwater irrigation at the tail end of canals is common in Punjab, as these farmers do not receive an equitable share of surface water supplies from the canal network. Surface water shortages at critical crop stages force farmers to irrigate with marginal-quality groundwater to minimize losses. Unmanaged and unregulated groundwater use means that upstream areas experience rising water tables, whereas tail-end areas suffer increased salinity problems as a result of excessive use of poor-quality groundwater (Qureshi 2015). This is a significant issue in the doabs of Punjab and Sindh.

Groundwater supplies less than 20 percent of the agricultural needs in Sindh (Young et al. 2019), mainly because only 29 percent of the area has suitable groundwater for irrigation (Mott MacDonald and Partners 1990). Groundwater in Sindh is extracted via about 100,000 tube wells—about 86 percent of those are privately owned by farmers, and the remainder is in the public sector. Most of the privately owned tube wells are diesel powered, whereas those in the public sector are largely electric (Government of Pakistan 2012; Government of Sindh 2009). Farmers prefer diesel-operated tube wells over electric tube wells as the former ensure water availability during periods of frequent electricity blackouts or load shedding.

Fresh groundwater in Sindh found along the left bank of the Indus River is in the Ghotki, Khairpur, and the South and North Rohri areas. Farmers have installed shallow groundwater pumps to supplement canal water irrigation (van Steenbergen and Oliemans 1997). Access to groundwater has increased the cropping intensity from about 90 percent to about 160 percent, an overall 70 percent increase (Louis Berger Group Inc. and Indus Associated Consultants (Pvt.) Ltd. 2011). A survey of randomly selected farmers across four districts (Badin, Matiari, Mīrpur Khās, and Tando Allahyar) indicated that 23 percent of farmers were fully dependent on groundwater and 77 percent used both surface and groundwater for irrigation (Mangan et al. 2016). Outside canal command areas, particularly in the riverine areas, there is uncontrolled use of groundwater for irrigation. Much of this is from seepage from the Indus River, which leaves fresh groundwater that can be exploited with relative ease and supports extensive encroachment activities.

Across the Indus basin, farmers invest heavily in agricultural groundwater use, and tube wells are installed largely without government technical or financial support. Shah et al. (2003) estimated the investment in private tube wells as equivalent to US$430 million PRs.25 billion in 2003), compared to the annual benefits from agricultural production of about US$2.5 billion (Rs.150 billion). The investment cost appears not to include operation and maintenance expenses, which in 2003 were estimated at about another US$390 million annually (Qureshi, Shah, and Akhtar 2003). The lowering of the water table as a result of groundwater abstraction over the years has increased both installation and energy costs for tube wells (Qureshi et al. 2008). For example, the cost of installing tube wells in areas of water table depth greater than 24 meters was seven times higher than those areas where the water table depth was about 6 meters (Qureshi, Shah, and Akhtar 2003). In 2015, the capital cost to install a tube well and annual maintenance costs were PRs 300,000 (US$2,950) and PRs 25,187 (US$250), respectively (Mangan et al. 2016).

Although groundwater in the Indus basin is most heavily utilized in Punjab and Sindh, it also provides parts of Khyber Pakhtunkhwa (box 2.1) and Balochistan.

BOX 2.1. Groundwater Use in Khyber Pakhtunkhwa

Groundwater use in Khyber Pakhtunkhwa (KP) is less intensive than in Punjab and Sindh. Groundwater provides about 14 percent of irrigation water in KP, surface water provides about 83 percent, and springs provide the rest (ACE and Halcrow 2003). These authors estimated that about 14,000 tube wells provided domestic and irrigation water supplies in 2003. Low groundwater use is linked to the availability of surface water. The depth of groundwater in the mountainous areas also restricts its use. The substantial shallow groundwater resources of the Peshawar Valley were developed as a result of recharge from the extensive irrigation system and from the Kabul and Indus rivers. In the 1980s, the valley faced serious waterlogging problems and the Salinity Control and Land Reclamation Project (SCARP) provided relief.

The Bannu, Dera Ismail Khan, Karak, and Kohat districts in KP are low rainfall areas with poor surface water availability. Groundwater abstraction in excess of recharge in these districts has lowered water tables and contaminated groundwater by saltwater intrusion (IUCN 2000). These authors found that only the quality of shallow groundwater within the Kashad Algad Valley in the Bannu and Karak districts was good (dissolved salt content less than 1,500 parts per million). A large variation in groundwater quality exists in the Bannu basin outside the valley, where the dissolved salt concentrations vary from 350 to 3,000 parts per million. A study of the Buner district by Khan, Haq, and Saeed (2012) concluded that direct discharge of untreated effluent from the marble industry contaminates surface and groundwater.

Agricultural Water Uses Are under Pressure

Water availability and distribution problems in agriculture are likely to intensify for several reasons. Drier or hotter climates will increase evapotranspiration and require more irrigation. Water reallocation from the agriculture to the domestic sector is almost inevitable as human needs for drinking water and hygiene will take priority over cropping. This reallocation is already underway as 37 cubic metres per second (1,200 cubic feet per second) of irrigation water are already being diverted from Keenjhar Lake to Karachi city and a feasibility study by the Sindh government is in progress to increase this by the same amount. This will cause an irrigation water shortage of the same amount for the command area in Thatta district.[3] The government of Punjab is also planning to divert 8 to 14 cubic meters per second from the Bambanwala-Ravi-Bedian Doab (BRBD) Canal to Lahore City and has already been coordinating with the Asian Infrastructure Investment Bank (AIIB) to finance the project.[4] Expanding water requirements for households and the industrial sector will further pressure agricultural water use. It is likely that irrigators will have no option but to turn to groundwater or shift to more efficient cropping patterns.

Domestic and Municipal Water Uses

Current 2017 and future 2050 domestic water demand in Pakistan has been estimated (as shown in table 2.2) using projected population figures (table 2.1) and guideline daily per capita requirements for urban (120 liters) and rural (45 liters) populations in accordance with Pakistan's National Drinking Water Policy (Government of Pakistan 2009). These show that domestic water use—drinking, cooking, cleaning, washing, ablution, and sanitation—in Pakistan will almost double over this period. The figures for domestic water demand shown in table 2.2 are based on policy commitments (National Drinking Water Policy, Government of Pakistan, 2009) and lower than those reported by Amir and Habib (2015), as shown in table 1.1. This reflects differences in population projections, particularly the urban-rural split.

Domestic Groundwater Use in Urban Areas

Other than Hyderabad, Islamabad, and Karachi, all major cities in Pakistan depend mainly on groundwater for household water supplies, and about 70 percent of the drinking water in Pakistan is supplied from groundwater (Chandio, Abdullah, and Tahir 1999). Even for those cities that rely on surface water for public supply, there is at least anecdotal evidence of private groundwater use for domestic purposes.

Rural to urban migration for livelihood opportunities has meant Pakistan's urban population has grown at a faster rate than the national population's. The population in major cities increased from 23.41 million in 1998 to 40.92 million in 2017, an increase of nearly 75 percent (table 2.3). This growth was most pronounced in Lahore (116.3 percent), Peshawar (101.0 percent), and Islamabad (94.2 percent).

There is no way to prevent this urban growth from increasing demand on groundwater resources, either by the cities directly extracting more groundwater to meet increasing demand or by them claiming agricultural canal water that will drive farmers to increase groundwater use. Total water availability is finite, and domestic supplies will inevitably take priority over the agriculture sector (UNDP 2017).

A survey conducted as part of a study on forecasting water demand under changing socioeconomic conditions (Bhatti and Nasu 2010) provides evidence of the challenge of quantifying demand for the

TABLE 2.2. Annual Domestic Water Demand and Projections for Urban and Rural Households

	Annual domestic water demand, 2017 (BCM)			Projected annual domestic water demand, 2050 (BCM)		
Description	**Urban**	**Rural**	**Total**	**Urban**	**Rural**	**Total**
Pakistan	3.31	2.17	5.48	7.70	2.66	10.36
Balochistan	0.15	0.15	0.30	0.46	0.16	0.62
FATA	0.01	0.08	0.09	0.19	0.06	0.25
KP	0.25	0.41	0.66	1.13	0.39	1.52
Punjab	1.77	1.14	2.91	4.08	1.41	5.49
Sindh	1.09	0.38	1.47	1.77	0.61	2.39
Islamabad	0.04	0.02	0.06	0.07	0.03	0.10

Source: Water demand estimated from population figures shown in table 2.1, and water demand as per Pakistan's National Drinking Water Policy (Government of Pakistan 2009).
Note: BCM = billion cubic meters; FATA = Federally Administered Tribal Areas; KP = Khyber Pakhtunkhwa.
Urban water demand = 120 liters per person per day, rural water demand = 45 liters per person per day.

TABLE 2.3. Population Growth of Major Cities in Pakistan

Major cities	Census, 1998 (million)	Census, 2017 (million)	Percentage increase	Main source of water supply
Karachi	9.33	14.91	59.8	Surface water
Lahore	5.14	11.12	116.3	Groundwater
Faisalabad (municipality)	2.00	3.20	60.0	Groundwater
Rawalpindi	1.40	2.09	49.3	Groundwater
Gujranwala (municipality)	1.13	2.02	78.8	Groundwater
Peshawar	0.98	1.97	101.0	Groundwater
Multan (municipality)	1.19	1.87	57.1	Groundwater
Hyderabad	1.16	1.73	49.1	Surface water
Islamabad (municipality)	0.52	1.01	94.2	Surface water
Quetta	0.56	1.00	78.6	Groundwater
Total	23.41	40.92	74.8	

Source: Pakistan Census Data (Pakistan Bureau of Statistics)

domestic urban context. The authors conducted a survey of domestic water use in 80 to 100 urban households in Faisalabad, Lahore, and Rawalpindi in both low- and high-income groups. There was great variation in usage, as shown in the next table, and it was found that water demand of high-income groups was about double that of low-income groups.

Domestic purpose	Usage (lppd)
Bath/shower	15–150
Cooking	5–45
Drinking	2
Toilet	5–60
Range	**22–257**

Note: Figures for laundry and gardening not provided, though these were mentioned as additional domestic uses. lppd = liters per person per day.

Although noting the similarity of these usage results with other studies, the authors also alluded to the difficulty in obtaining reliable results and the need to conduct more extensive surveys. The variation in usage figures reflects the challenge of accurately estimating water demand in a system in which almost nothing is measured and identifies a dilemma for Pakistan in planning and provisioning adequate domestic water supplies for its current and growing population.

Water consumption in major cities in Pakistan and neighboring India was estimated as 300 liters per person per day (Shaban and Sharma 2007), but this figure included both domestic and commercial uses and probably also nonrevenue water (leaks and theft).

Bhatti and Nasu (2010) showed unaccounted water (leakage and unauthorized connections) was 40 percent for Faisalabad, 40 percent for Rawalpindi, and 34 percent for Lahore, compared with 17 percent in Beijing, China, and 7 percent in Osaka, Japan. The projected water demand for the domestic subsector may, therefore, be largely met by reducing unaccounted water flows and managing demand. Because about 70 percent of domestic water needs are met from groundwater (Chandio, Abdullah, and Tahir 1999), reducing unaccounted water demand would significantly benefit groundwater, though reducing unaccounted flows from supply pipe leakage may serve to reduce urban groundwater recharge.

Domestic Groundwater Use in Rural Areas

Current and projected demand for rural domestic water is shown in table 2.2. Despite its larger size, the rural population is estimated to use about two-thirds of the water used by the urban population. More than 90 percent of rural households in Punjab and Sindh depend on groundwater, accessing the resource via many thousands of hand-powered and motorized pumps (Young et al. 2019). More than 70 percent of rural households in Balochistan and Khyber Pakhtunkhwa are without piped water (Mansuri et al. 2018), and a substantial proportion of these rely on springs, wells, tube wells, and other groundwater sources, extracted principally by hand pumps and motorized pumps.

In some rural areas in Punjab and Sindh, seepage from irrigation canals supports fresh groundwater lenses in areas where groundwater salinities are otherwise high, which in turn provide drinking water to villages and towns (Ensink et al. 2002; Jensen et al. 1998). This has implications for the management of canal water, including the proposed lining of some canals to reduce seepage and for the careful management of the lens of fresh seepage water that sits atop the saline groundwater.

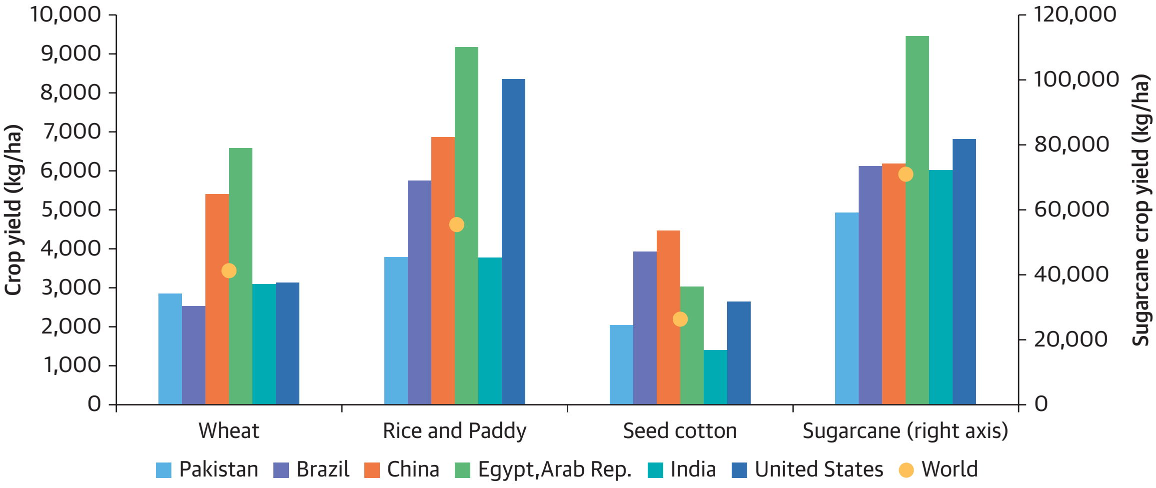
Agricultural Yield in the Indus Basin

The yields of major crops in Pakistan's Indus basin are low compared to similar environments in China, Egypt, and India (figure 2.3). For example, Pakistan's average wheat yield per hectare between 2013 and 2017 was 51 percent of China's.

Pakistan's poor yield gap (see table 2.4) shows opportunity for improving agricultural productivity.

Pakistan will need to increase crop yields per unit of water used to improve agricultural water productivity, which will require significant improvement in water use efficiency. Pakistan's agricultural water productivity lags behind that of most other countries (see figure 2.4), including that of neighboring India. Young et al. (2019) indicated that major reforms are required in the water sector to allow Pakistan to make significant improvements in agricultural water productivity. Without this increase, Pakistan would see continued slow economic growth with a projected US$2,200 GDP per capita by 2047 (Young et al. 2019). Achieving higher agricultural water productivity would also improve groundwater conservation and sustainability.

FIGURE 2.3. Yield of Major Crops in the Leading Agricultural Economies



Source: Data are averages of the yield from 2014 to 2018 from FAOSTAT (2020), Crop Statistics, http://www.fao.org/faostat/en/#data/QC, Food and Agriculture Organization of the United Nations (FAO), Rome, accessed 31 August 2020
Note: kg/ha = kilogram per hectare.

TABLE 2.4. Yield Gap (Major Crops)

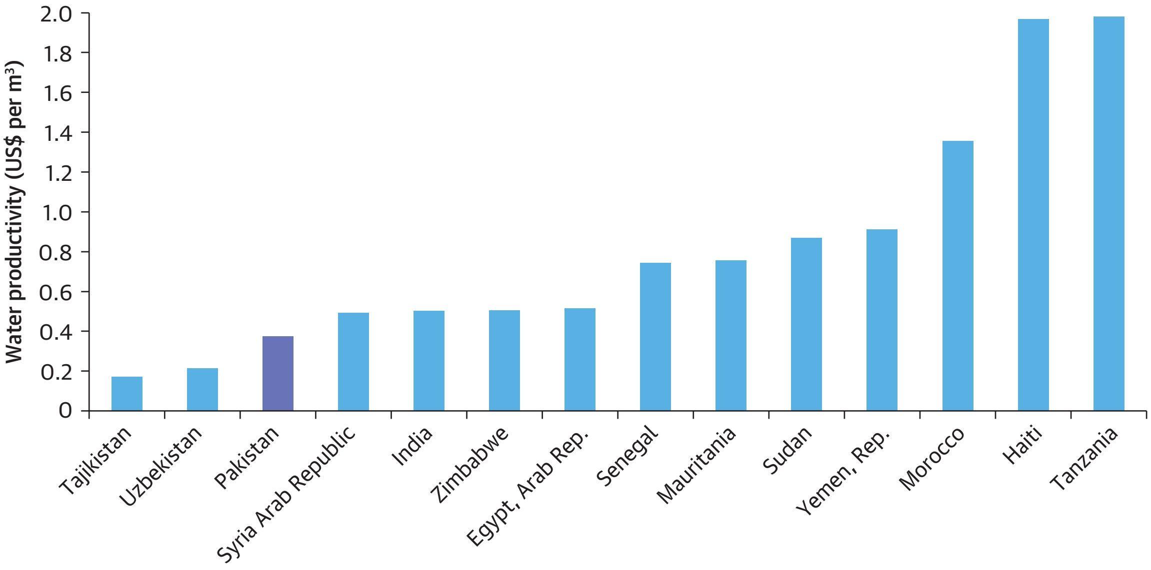
Country	Wheat (kg/ha)	Difference from best[a] (%)	Sugarcane (kg/ha)	Difference from best[a] (%)	Rice (paddy) (kg/ha)	Difference from best[a] (%)	Cottonseed (kg/ha)	Difference from best[a] (%)
World	3,086	65	71,510	59	4,309	44	2,099	54
Brazil	—	—	79,709	66	4,229	44	3,757	96
China	**4,762**	**100**	73,114	60	6,556	67	**3,906**	**100**
Egypt, Arab Rep.	—	—	**121,136**	**100**	**9,731**	**100**	2,333	60
India	2,802	59	68,877	57	3,370	35	1,206	31
Pakistan	2,451	52	51,494	43	3,520	36	2,046	52
United States	3,018	63	73,765	61	7,672	79	2,250	58

Source: Government of Pakistan 2018.
Note: Data pertain to 2008. kg/ha = kilogram per hectare; — = no data
a. Best = 100.

Industrial Groundwater Use

In Pakistan, large industries are located near cities and towns. Industrial complexes were built near Gadoon Ahmazai and Hattar in Khyber Pakhtunkhwa; Chunian, Kala Shah Kaku, Sundar, and Taxila in Punjab; as well as Hub Industrial Estate in Sindh. Small industries were also set up in small towns and periurban areas. The dominant industries are textiles, chemicals, fertilizers, automobiles, tanneries,

FIGURE 2.4. **Agricultural Water Productivity in Selected Countries**



Source: Young et al. 2019.
Note: m^3 = cubic meter.

sugar, cement, and mining. Textiles is the largest industrial sector, employing 40 percent of the industrial labor force and generating 25 percent of industrial gross domestic product (GDP) and 57 percent of exports by value (Young et al 2019). Soft drink and water bottling plants are also present in several of these locations, and several of them use groundwater as a raw product. Public perception is that bottled water companies extract large amounts of water, pay little for it, and cause groundwater depletion (*Dawn* 2018). The truth of these perceptions cannot be tested in the absence of publicly available data for the aquifer (not just the site of bottled water extractions).

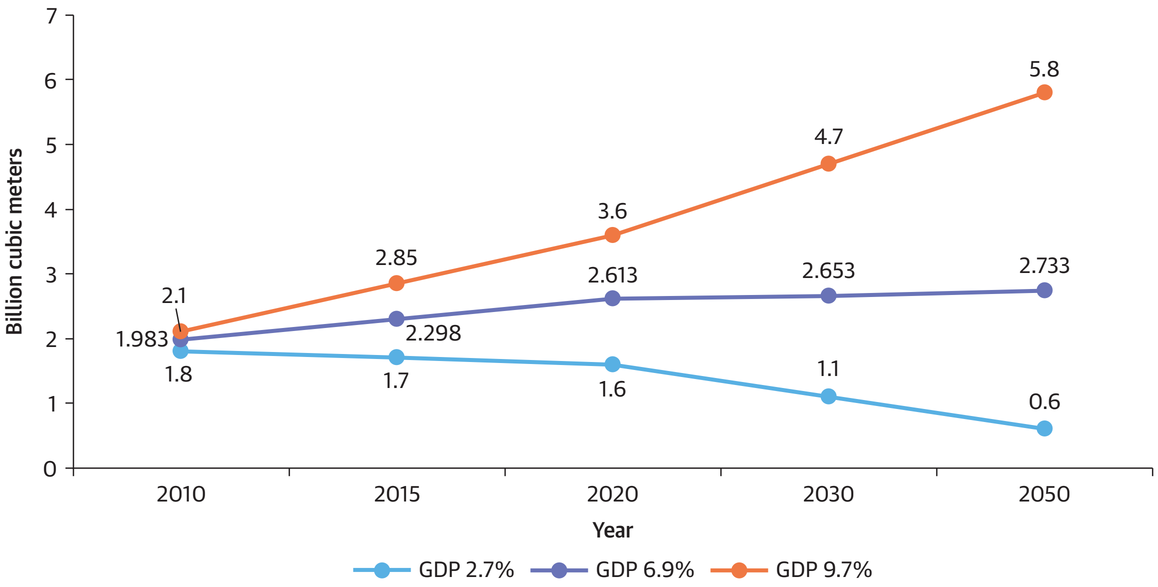
Groundwater is the main source of industrial water use and accounts for about 80 percent of the total industrial water demand. It is used in almost all industrial areas except those located near Hyderabad Islamabad, and Karachi, which mainly use surface water (though localized industrial use of groundwater in Karachi is now controlled under permit by the Karachi Water and Sewage Board[5]). Industrial water use increased from 1.534 billion cubic meters in 1975 to 3.47 billion cubic meters in 2000. Its subsequent decline to 1.4 billion cubic meters in 2008 (FAO 2012) was attributed to the energy crisis that shut down many industry operators at that time (table 2.5). Since those estimates, increased energy supply and government initiatives promoting industrial growth have raised industrial water demand estimates to 4.0 billion cubic meters in 2025 and 8.4 billion cubic meters in 2050 (Amir and Habib 2015). These figures are much higher than estimates under the National Water Strategy 2002, reflecting rapid growth in energy availability and the revival of industry in Pakistan.

TABLE 2.5. **Historical Water Uses by Sector**

Year	Agriculture (BCM)	Industrial (BCM)	(BCM)	Total water withdrawal (BCM)
1975	150.30	1.534	1.534	153.40
1991	150.60	2.50	2.50	155.60
2000	162.70	3.47	6.39	172.60
2008	172.40	1.40	9.65	183.50

Source: FAO (Food and Agriculture Organization) AQUASTAT (database), United Nations http://www.fao.org/nr/water/aquastat/data/query/results.html
Note: BCM = billion cubic meters.

FIGURE 2.5. **Projection of Industrial Water Demand in Pakistan for Three GDP Growth Rates**



Source: UNDP 2017.
Note: GDP = growth domestic product.

UNDP (2015) projected industrial water demand for 2030 and 2050 in three economic development scenarios. These estimates (figure 2.5) show decreasing water demand from 1.8 billion cubic meters in 2010 to 0.6 billion cubic meters in 2050 for the slow GDP growth projection of 2.7 percent; an increasing trend from 1.983 billion cubic meters in 2010 to 2.733 billion cubic meters in 2050 for the medium GDP growth projection of 6.9 percent; and significant increase from 2.1 billion cubic meters per year in 2010 to 5.8 billion cubic meters per year in 2050 for the high GDP growth projection of 9.7 percent. Climate change will also affect industrial water demand, and a faster warming scenario could increase industrial demand by more than 20 percent by 2050 (Young et al. 2019).

Comparing Sectoral Uses of Groundwater

Historical water use data from the Food and Agriculture Organization (FAO) (table 2.5) show a steady increase in the agriculture, industrial, and municipal sectors. Agricultural water use increased by 14.7 percent from 1975 to 2008. By comparison, municipal water use increased by more than five times in the same period. Agricultural water use was 98 percent of total use in 1975 but declined to 94 percent in 2008. UNDP-Pakistan (2017) estimated water demand for those three sectors for four future scenarios, including business as usual, moderate demand management, strong demand management, and climate change.[6] Table 2.6 presents projection comparisons for moderate demand management with climate change as these management response options are the most likely for the foreseeable future. Both scenarios indicate a growth in water use, and both assume more water will be available. If this growth is to be realized, thought must be given to where and how this water is going to be sourced without jeopardizing human health and food production. Differences in baseline values between tables 2.6 and 1.1 arise from different underlying assumptions, reflecting the challenge of working without baseline measurements. Common to all predictions is the increase in water use across all sectors.

Urban growth, changes in city lifestyles, increases in industrial water demand, and demand from smallholder farmers have all contributed to greater groundwater extraction in the past. This suggests a proportionate increase in groundwater demand in the future, placing additional pressure on aquifers, particularly in areas under stress.

Groundwater already composes more than 50 percent of irrigation water demand in Punjab, as much as 20 percent of irrigation water demand in Sindh, and about 70 percent of domestic and industrial water demand. An increase in the latter is predicted, with the balance likely to come from groundwater. This will mean a reduction in agricultural water, running counter to agricultural demand under many climate change scenarios, and is likely to result in crop stress, which will have to be managed through climate adaptation measures.

TABLE 2.6. UNDP-Pakistan Estimates for Three Water Use Sectors and for Two Scenarios

	Moderate demand management				Climate change scenario			
Year	Agriculture (BCM)	Industrial (BCM)	Municipal (BCM)	Total water withdrawal (BCM)	Agriculture (BCM)	Industrial (BCM)	Municipal (BCM)	Total water withdrawal (BCM)
2015	173.00	2.30	5.11	180.41	173.00	2.30	5.11	180.41
2030	166.00	2.65	7.15	175.80	187.60	2.65	7.58	197.83
2050	170.80	2.73	9.96	183.19	206.20	2.73	10.66	219.59

Source: UNDP-Pakistan 2017.
Note: BCM = billion cubic meters.

Notes

1. The estimated population was 66,816,877 in 1975 and 171,684,986 in 2008. Pakistan's population clock can be accessed at https://www.worldometers.info/world-population/pakistan-population/.

2. *Conjunctive use* of surface water and groundwater means using water from both sources in an opportunistic manner according to personal convenience. *Conjunctive management* refers to a strategic approach—for example, at the irrigation command level, where surface water and groundwater use are managed together and optimized for the benefit of users and the effective management of water resources.

3. Feasibility study prepared by National Engineering Services Pakistan for the government of Sindh.

4. Project is being undertaken by the government of Punjab with support from the AIIB.

5. See *The Sindh Government Gazette*, September 28, 2018, at http://www.kwsb.gos.pk/SitePdfFiles/GAZETTE28.pdf.

6. Differences in analysis between Ali (2018) and UNDP-Pakistan (2017) reflect that the latter was based on 120 liters per person per day and 1998 population figures, whereas the former used 100 liters per person per day and 2017 census data.

References

ACE (Associated Consulting Engineers), EGC (Engineering General Consultants), and SMEC International. 2011. Nationwide Study of Groundwater Availability and Conjunctive Management. Volume 1 Main Report. Ministry of Water and Power, Project Management and Policy Implementation Unit, Government of Pakistan.Lahore.

ACE (Associated Consulting Engineers) and HALCROW. 2003. *Exploitation and Regulation of Fresh Groundwater.* Report prepared for Federal Flood Commission, Islamabad. Accessed in 2019 from ACE Library, Lahore, Pakistan.

Alam, U., Parminder Sahota, and Paul Jeffrey. 2007. "Irrigation in the Indus Basin: A History of Unsustainability?" *Water Science and Technology Water Supply* 7 (1): 211-218.

Ali, A. 2018. "Improving Salinity and Agricultural Water Management in the Indus Basin, Pakistan: Issues, Management and Opportunities. A Synthesis from Desktop Literature Review." ACIAR-Financed Short-Time Research Activity for Preparing the Project on Management of Salinity and Agricultural Water Management in the Pakistan's Indus Basin.

Amir, P., and Z. Habib. 2015. "Estimating the Impacts of Climate Change on Sectoral Water Demand in Pakistan." ACT Report, Action on Climate Today, Nottinghamshire, U.K. Accessed March 2019. https://cyphynets.lums.edu.pk/images/Readings_concluding.pdf.

Bhatti, A. M., and S. Nasu. 2010. "Domestic Water Demand Forecasting and Management Under Changing Socio-Economic Scenario for Pakistan." Society for Social Management Systems (SSMS-2010). Accessed April 11, 2019. https://waterinfo.net.pk/sites/default/files/knowledge/Domestic%20Water%20Demand%20Forecasting%20and%20Management%20Under%20Changing%20Socio-Economic.pdf.

Chandio, B. A., M. Abdullah, and M. A. Tahir. 1999. "Drinking Water Quality and Standardization in Pakistan" in Proceedings of the National Workshop on Quality of Drinking Water, Islamabad, March 7, 1998. https://www.ircwash.org/sites/default/files/242-15920.pdf

Dawn. 2018. "Bottled Water Firms Ordered to Pay Price of Groundwater." December 4, https://www.dawn.com/news/1449318/bottled-water-firms-ordered-to-pay-price-of-groundwater.

Ensink, J. H. J., M. R. Aslam, F. Konradsen, P. K. Jensen, and W. van der Hoek. 2002. "Linkages between Irrigation and Drinking Water in Pakistan." IWMI Working Paper 46, International Water Management Institute, Colombo, Sri Lanka.

FAO (Food and Agriculture Organization). 2012. *Irrigation in Southern and Eastern Asia in Figures. AQUASTAT Survey - 2011. FAO Water Reports 37,* edited by Karen Frenken, FAO Land and Water Division. Accessed April 12, 2019. http://www.fao.org/nr/water/aquastat/data/query/results.html.

Friends of Democratic Pakistan. 2012. A Productive and Water-Secure Pakistan: Infrastructure, Institutions, Strategy. A Report of the Water Sector Task Force of the Friends of Democratic Pakistan, Islamabad. https://metameta.nl/wp-content/uploads/2013/11/FoDP-WSTF-Report-Final-09-29-12.pdf

Government of Pakistan. 2009. *National Drinking Water Policy.* Ministry of Environment, Government of Pakistan, Islamabad.

——. 2012. *Agricultural Statistics of Pakistan.* Statistics Division, Government of Pakistan, Islamabad.

——. 2014. *Agricultural Statistics of Pakistan.* Ministry of Food and Agricultural and Livestock, Government of Pakistan, Islamabad.

——. Government of Pakistan. 2017. Statistical Year Book, 2017. Pakistan Bureau of Statistics. Islamabad.

——. 2018. "Chapter 2: Agriculture." In *Economic Survey 2017-18.* Economic Adviser's Wing, Finance Division, Government of Pakistan, Islamabad. Accessed April 9, 2018. http://www.finance.gov.pk/survey/chapters_18/12-Population.pdf and http://www.finance.gov.pk/survey_1718.html.

Government of Sindh. 2009. *Agricultural Statistics of Sindh.* Agricultural Extension Department, Government of Sindh. http://sindhbos.gov.pk/wp-content/uploads/2013/12/Agriculture-Statistics-of-Sindh-2009.pdf.

IUCN (International Union for Conservation of Nature). 2000. "Pakistan Water Situation Analysis for World Commission on Dams during Consultative Process for Pakistan and Supported by Royal Netherland Embassy in Pakistan."

Jehangir, W. A., H. Turral, and S. Khan. 2003. "Net Gains from Conjunctive Use of Surface and Ground Water." *Pakistan Development Review* 42 (4): 823–38. https://doi.org/10.30541/v42i4IIpp.823-38.

Jensen, P. K., W. van der Hoek, F. Konradsen, and W. A. Jehangir. 1998. "Domestic Use of Irrigation Water in Punjab" IN: Pickford, J. (ed). Sanitation and water for all: Proceedings of the 24th WEDC International Conference, Islamabad, Pakistan, 31 August-4 September 1998, pp.297-299

Khan, S., F. Haq, and K. Saeed. 2012. "Pollution Load in Industrial Effluent and Groundwater Due to Marble Industry in District Buner, Khyber Pakhtunkhwa, Pakistan." *International Journal of Recent Scientific Research* 3 (5): 366-368. Accessed May 2019. http://www.recentscientific.com.

Louis Berger Group Inc. and Indus Associated Consultants (Pvt.) Ltd., 2011. "Preparation of Regional Plan for the Left Bank of Indus, Delta and Coastal Zone." Sindh Water Sector Improvement Project Phase-I (WSIP-I), Sindh Irrigation and Drainage Authority.

Mangan, T., G. M. Nangraj, N. Laghari, A. A. Khooharo, and R. A. Buriro. 2016. "Use of Underground Water and Its Impact on Agriculture of Sindh." *Pakistan Journal of Social Sciences* 36 (2): 761–70. https://www.bzu.edu.pk/PJSS/Vol36No22016/PJSS-Vol36-No2-14.pdf.

Mansuri, Ghazala, Mohammad Farhanullah Sami, Muhammad Ali, Hang Thi Thu Doan, Bilal Javed, and Priyanka Pandey. 2018. "When Water Becomes a Hazard: A Diagnostic Report on The State of Water Supply, Sanitation and Poverty in Pakistan and Its Impact on Child Stunting" (English). WASH Poverty Diagnostic Series, World Bank, Washington, DC. http://documents.worldbank.org/curated/en/649341541535842288/When-Water-Becomes-a-Hazard-A-Diagnostic-Report-on-The-State-of-Water-Supply-Sanitation-and-Poverty-in-Pakistan-and-Its-Impact-on-Child-Stunting.

Mohammad, G., and C. Beringer. 1963. "Waterlogging and Salinity in West Pakistan: An Analysis of the Revelle Report." *The Pakistan Development Review* 3 (2): 250–78.

Mott MacDonald and Partners. 1990. *Water Sector Investment Planning Study, Vol. 1.* Harza Engineering International and National Engineering Services of Pakistan, Government of Pakistan.

Pakistan Bureau of Statistics. Population census data. http://www.pbs.gov.pk/content/population-census.

1998 population census data found at: http://www.pbs.gov.pk/sites/default/files//tables/POPULATION%20SIZE%20AND%20GROWTH%20OF%20MAJOR%20CITIES.pdf

2017 population census data found at: http://www.pbs.gov.pk/content/block-wise-provisional-summary-results-6th-population-housing-census-2017-january-03-2018

Qureshi, A. S. 2015. "Improving Food Security and Livelihood Resilience through Groundwater Management in Pakistan." *Global Advanced Research Journal of Agricultural Science* 4 (10): 687–710.

Qureshi, A. S., M. A. Gill, and A. Sarwar. 2008. "Sustainable Groundwater Management in Pakistan: Challenges and Opportunities." *Irrigation and Drainage* 59 (2): 107–06. https://doi.org/0.1002/ird.455.

Qureshi, A. S., T. Shah, and M. Akhtar. 2003. "The Groundwater Economy of Pakistan." Working Paper 64, International Water Management Institute, Lahore, Pakistan.

Shah, T., A. D. Roy, A. S. Qureshi, and J. Wang. 2003. "Sustaining Asia's Groundwater Boom: An Overview of Issues And Evidence." *Natural Resources Forum* 27 (2): 130–41. doi:10.1111/1477-8947.00048.

Shaban, A., and R. N. Sharma. 2007. "Water Consumption Patterns in Domestic Households in Major Cities." *Economic & Political Weekly*, June 9.

UNDP-Pakistan. 2017. The Vulnerability of Pakistan's Water Sector to the Impacts of Climate Change: Identification of gaps and recommendations for action. https://www.pk.undp.org/content/pakistan/en/home/library/environment_energy/PakistanWaterSectorReport.html

van Steenbergen, F., and W. Oliemans. 1997. "Groundwater Resource Management in Pakistan." In ILRI Workshop "Groundwater Management: Sharing Responsibility for an Open Access Resource," Proceedings of the Wageningen Water Workshop 1997, Wageningen, The Netherlands.

Young, W. J., A. Anwar, T. Bhatti, E. Borgomeo, S. Davies, W. R. Garthwaite, E. M. Gilmont, C. Leb, L. Lytton, I. Makin, and B. Saeed. 2019. "Pakistan: Getting More from Water." Water Security Diagnostic, World Bank, Washington, DC. http://documents1.worldbank.org/curated/en/251191548275645649/pdf/133964-WP-PUBLIC-ADD-SERIES-22-1-2019-18-56-25-W.pdf

Chapter 3
Understanding the Groundwater Resource

Key Points

- Groundwater in Pakistan's Indus basin represents the largest volume of freshwater storage in the country, with an estimated volume of more than 1,200 billion cubic meters. The aquifer is part of the Indo-Gangetic basin that drains the Indus, Ganges, and Brahmaputra rivers and is a globally important transboundary water resource.
- Average annual renewable groundwater is estimated at 61 billion cubic meters, of which 44 billion cubic meters is recirculated water from canal seepage or irrigation return flows.
- The aquifer consists of a heterogeneous distribution and thickness of unconsolidated sands, silts, and clays with minor gravels. As a transmissive, unconfined, and shallow aquifer, the water resource is both easily accessible for abstraction and easily penetrated by contaminants and pollutants.
- Salinity is a major quality issue affecting groundwater in the Indus basin and worsened by waterlogging and evaporative concentration of salts in irrigation water. The total additional influx of salt to the aquifer from canal irrigation is estimated to be about 16 million tons per annum.
- Deteriorating groundwater quality is widespread, and most of the cities and towns in the Indus basin suffer from low-quality drinking water. Unsafe drinking water affects as much as 80 percent of the population of Pakistan. Microbial contamination of drinking water is a major problem, as well as salinity, arsenic, fluoride, and agricultural and industrial contaminants.
- Because of the connected nature of all water resources in the Indus basin, and the time required to remediate contaminated groundwater, deteriorating groundwater quality poses a long-term threat to Pakistan's water resource base.

Topography and Rainfall

The 520,000 square kilometers of the Indus River basin in Pakistan are bounded by Himalayan piedmont to the north and the Arabian Sea in the south. The average land slope is a 1-meter fall in about 5 kilometers. The upper Indus basin is drained by its tributaries (the Jhelum, Chenab, Ravi, Beas and Sutlej rivers), which divide the plain into interfluvial systems of fertile land in Punjab. The confluence of Chenab River with Indus (where all the tributaries terminate) near Mithankot in Punjab marks the downstream boundary of the upper Indus plain. Many cities and towns are located along these tributaries. The land between two tributary rivers (called doab) is fertile, having good groundwater recharge potential and offering most of the livelihood opportunities for farming families in Punjab.

The lower Indus plain (the entire area downstream of the junction of the Chenab River with the Indus) is drained by a single river channel extending through part of southern Punjab and Sindh. The slope is flat (1 meter in 10 kilometers), and the river flows along a ridge above the surrounding land and recharges the aquifer in a narrow belt beside the river. Flooding is a common problem.

Outcrops of limestone near the towns of Sukkur and Hyderabad and several freshwater lakes, including Hamal, Manchar and Keenjhar are the main natural features in the lower Indus plain. The Indus River flows as a regular single channel to the town of Thatta and then forms several tributaries downstream as it spreads into the deltaic plain before it flows into the Arabian Sea.

Although the variation in topography of the Indus basin gives rise to a range of climates, the largest area of the Indus basin in Pakistan, the plains of Punjab and Sindh, experience semiarid monsoonal conditions. Although annual rainfall can peak at 2,000 millimeters on the mountain slopes, the average annual precipitation in the lowlands ranges between 100 and 500 millimeters. Thus, snowfall at higher altitudes (above 2,500 meters) accounts for most of the river runoff (FAO 2012), ensuring relatively stable interannual flow in the Indus despite variable annual rainfall (Young et al. 2019). At the basin scale, 60 percent of the annual precipitation falls between July and September (Young et al. 2019), 17 percent in winter, with the balance falling in spring and autumn.[1] Over the period 1951–2000, a decrease of 10 to 15 percent in winter and summer rainfall in arid plains and coastal areas was observed, whereas an increase of 18 to 32 percent in summer rainfall was observed in the core monsoon region of Pakistan (Chaudry 2017). Seasonal trends influence water availability and uses (Fowler and Archer 2005). The mean maximum monthly temperatures of the lower plains during winter vary from 14°C to 20°C. During the summer months (March to June), mean maximums for the same areas vary from 42°C to 44°C. However, in the upper plain, the comparative winter variability is 2°C to 23°C, and summer variability is 23°C to 49°C.

Aquifer Overview

The Indus plain is underlain by deep deposits of unconsolidated, highly permeable alluvium consisting primarily of fine to medium sand, silt, and clay with minor gravels, which form a highly transmissive unconfined aquifer. This aquifer is part of the larger Indo-Gangetic aquifer, one of the world's most important transboundary water resources (Bonsor et al. 2017), which underlies the Indus, Ganges, and Brahmaputra rivers. In Pakistan, this aquifer covers about 31.5 million hectares, mostly in Punjab and Sindh provinces, which are the focus of this chapter. Areas of the aquifer outside of Punjab and Sindh include the northwest district of Dera Ismail Khan in Khyber Pakhtunkhwa and a small region on the western boundary of Sindh, which lies in Balochistan.[2]

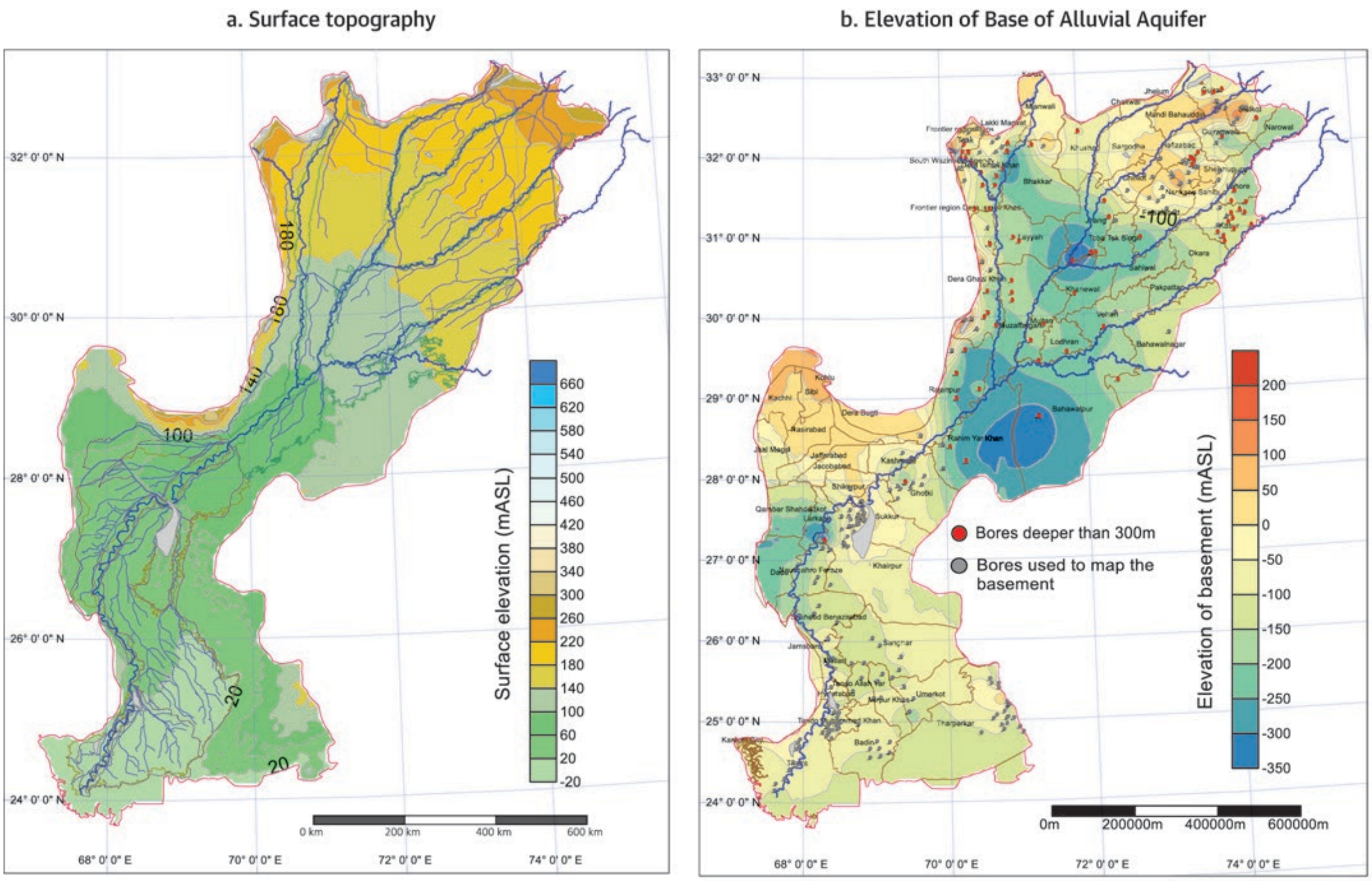
For this assessment, the Indus basin is considered to be a single unconfined aquifer, though individual sediment layers may be locally discontinuous or extensive such that locally there is a deeper, second aquifer. As an unconfined and shallow aquifer, the water resource is both easily accessible for abstraction and easily penetrated by contaminants and pollutants. Furthermore, the water level responds rapidly to recharge and discharge and is influenced by the network of canals and rivers.

An understanding of aquifer geometry and an assessment of aquifer parameters is necessary if the Indus basin aquifer is to be sustainably used to meet Pakistan's rising water demands.

Aquifer Geometry and Parameters

The geometry of the unconfined alluvial aquifer is defined by the ground surface and the base of the alluvial sediments, which are underlain by igneous and metamorphic basement of much lower average permeability. The surface layer defined by the topography, and basement elevation is shown in map 3.1, and within the alluvial part of the Indus basin in Pakistan, the surface topography varies from 654 meters to -4.3 meters above sea level (mASL). The thickness of the alluvial sediments in Punjab is reported to be in excess of 1,000 meters (ACE, AGC, and SMEC 2011). However, data available for this analysis indicated the greatest depth of sediments is 520 meters in Gujranwala district (Punjab) and 409 meters in Khairpur district (Sindh).

MAP 3.1. Surface Topography and Elevation of Base of Alluvial Aquifer



a. Surface topography

b. Elevation of Base of Alluvial Aquifer

Note: Topography uses Shuttle Radar Topography Mission (SRTM) 30-meter data. Gray areas on panel b are where the basement rises above the land surface to form hills. mASL = meters above sea level.

The grain size of the aquifer alluvium changes with increasing distance from the Himalaya, from coarse gravels and sands (85 percent) close to the mountains to medium sands (70 percent fine-medium sands) within the central parts of the Indus basin, grading to silts (70 percent) in the deltaic deposits in the coastal regions (Bonsor et al. 2017). Although the alluvium in the lower Indus basin is generally finer grained than that in the upper Indus basin, fine-grained deposits of low permeability are generally discontinuous, and variations are observed in the thickness of interbedded layers of sand, gravel, clay, and silt. These changes in grain size influence the rate of groundwater movement and the ability of the aquifer to store water.

The topography also influences shallow groundwater movement, and although the average slope for the whole basin is about 0.2 meters per kilometer, in Punjab it is closer to 0.3 meters per kilometer, in Upper Sindh it drops to 0.14 meters per kilometer, and in Lower Sindh to 0.10 meters per kilometer. This flattening out of slope from north to south contributes to notable differences in groundwater flow in the upper and lower parts of the Indus basin.

There are two prominent hilly outcrops within the basin: the crystalline basement outcrops that form the hills in Sargodha district and near Chiniot in Punjab and the sedimentary outcrops that form the Kirthar Hills in Khairpur and Sukkur districts in Sindh. The basin also has a number of smaller outcrops near the boundary of the alluvial aquifer.

The crystalline basement in Punjab forms a buried ridge (box 3.1), which may affect groundwater flow and salinity.

The assessment of groundwater resources in this report is based on drilling logs and water level and salinity measurements from boreholes and tube wells from across Punjab and Sindh. To interpret

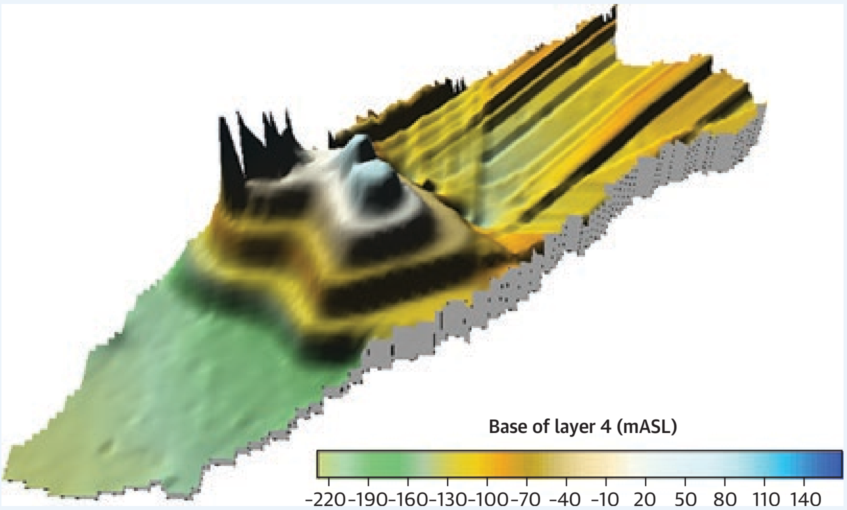
BOX 3.1. A Detailed Look at Basement Structure of the Chaj and Rachna Doabs

The basement of the alluvial deposits in Chaj Doab near Sargodha and in Rechna Doab near Chiniot represents the remnants of a buried ridge of indurated metamorphic and igneous rocks. These basement rocks also occur as isolated hills, known as the Kirana Hills, near the villages of Kirana in southern Chaj Doab and Chiniot, Sangla, and Shahkot in central Rechna Doab. These Precambrian consolidated rocks are exposed near Chiniot, Sangla, and Shahkot along the midwestern boundary of the doab (Chaudhry, Ahmed, and Mateen 1999). The largest of these outcrops is in the southern part of Sargodha district where the hills are spread over an area of 90 square kilometers. The northwesterly alignment of the Kirana Hills and associated outcrops form part of the Shahpur Delhi (or Sargodha) basement ridge (figure B3.1.1) that is largely buried by alluvium (Greenman, Swarzenski, and Bennett 1967). These crystalline rocks trend in a southeasterly direction, extending through the central part of the Chaj Doab from near Sargodha beneath Kirana and into Rechna Doab beneath Chiniot, Mangtanwala, Sangla, and Shahkot.

box continues next page

BOX 3.1. continued

FIGURE B3.1.1. Basement Structure for Rechna Doab



Source: After Punthakey et al. 2015.
Note: mASL = metres above sea level.

The borelog (E-29-R) close to the left bank of the Chenab River shows the top of the buried bedrock ridge at 128 meters below ground level in Chiniot district. The alluvial fill was deposited in subsiding troughs by the ancestral and present tributaries of the Indus River system (Khan 1978, and cited in Waqar et al. 2002). This effectively divides the unconfined aquifer of the Rechna Doab into two subbasins, composing the upper and lower reaches of the doab, though it does not prevent the regional flow of groundwater across and over the ridge. Further evidence of this is noted from the depth of bore SPL-71-A-R, which reaches a depth of 458 meters in Nankana Sahib district about 38 kilometers northeast of the bedrock outcrop on the border of Faisalabad and Nankana Sahib districts.

Similarly, about 90 kilometers toward the southwest of the bedrock hills, bore SPL-28-R drilled to a depth of 424 meters indicates a sharp increase in the depth of the aquifer away from the bedrock ridge. Furthermore, SPL-28-R in Faisalabad district has not reached bedrock despite reaching a depth of 424 meters. The sharp drop in the basement topography on both sides of the bedrock ridge is an important feature, effectively partitioning the upper and lower reaches of Rechna Doab. Improved understanding of the water and salt balance for these subbasins will provide guidance for improved management of groundwater resources in the upper and lower Rechna Doab. See appendix B for representative borelog diagrams.

aquifer parameters for the Indus basin alluvium, a database of 1,496 bores and associated borelogs (Punthakey et al. 2017) was used, with data from as many bores as possible included to ensure adequate spatial coverage. As shown in map 3.2, almost all the bores are in the canal command areas of Punjab and Sindh. Outside these areas, there are a handful of bores in the Cholistan Desert and in Tharparkar district of the Thar Desert. There is an extensive area of the Indus basin along Pakistan's eastern border that has very few bores.

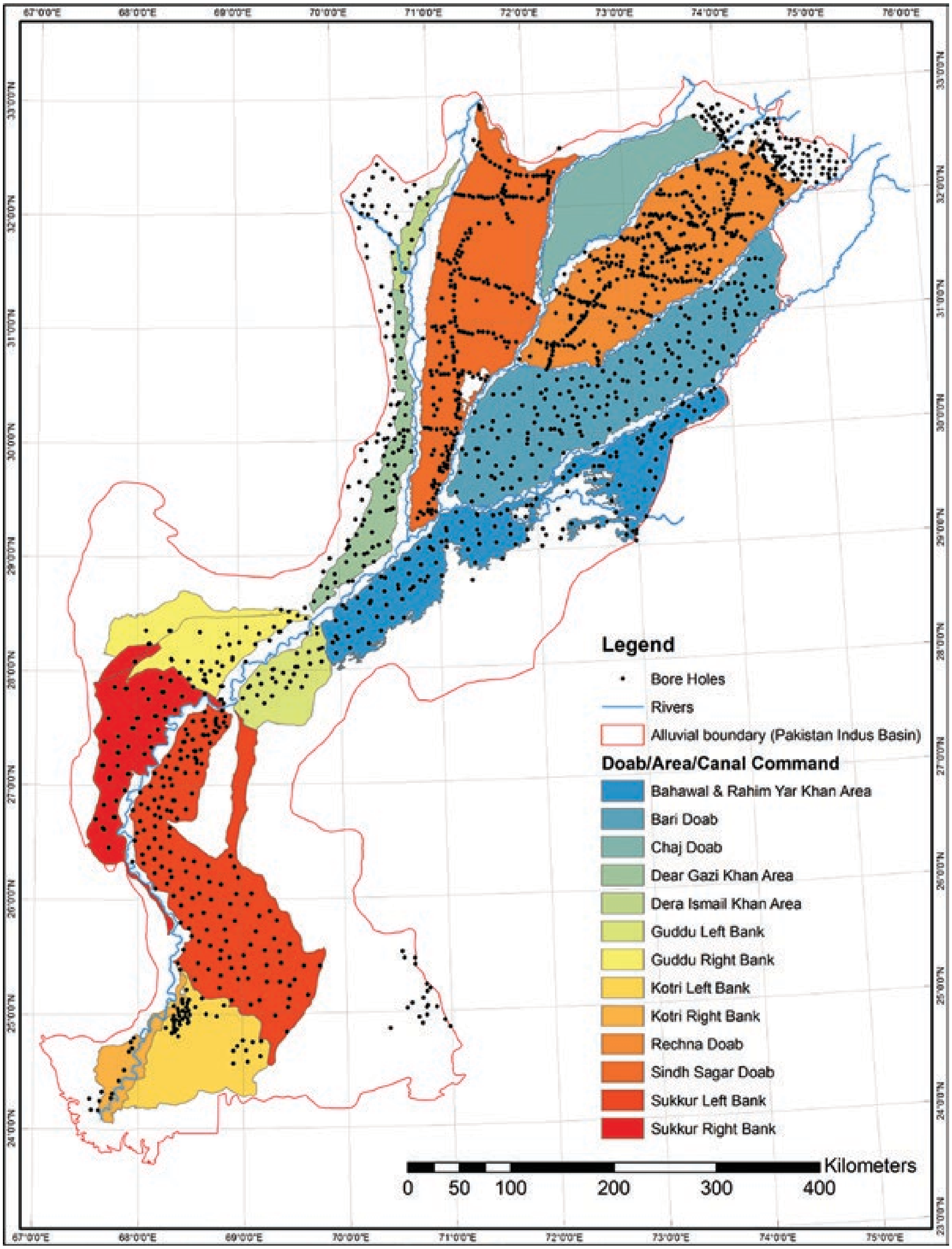
Data from the available borelogs (Punthakey et al. 2017) were analyzed based on their lithology to estimate hydraulic conductivity (K), a measure of water movement, and specific yield (S_y), a measure of storage capacity—both functions of sediment characteristics. These estimates are critical to groundwater management as they determine important values, such as transmissivity of the alluvium (the ability to transmit water as a function of K and aquifer thickness), as shown in map 3.3, and its potential for water storage. This assessment indicates the basin has relatively high hydraulic conductivities and reasonably good storage potential and that relatively higher transmissivities are found in the Bari Doab, Khanewal, and Pakpattan districts of Punjab, where bores are deeper as compared with most of Sindh.

The estimated K from the upper to the lower reaches of the Indus basin ranges from 126 to 2 meters per day (map 3.4) with median value of 59 meters per day. This is derived from borelog information for depths up to 500 meters, which may explain why the range is larger than that reported elsewhere. Bonsor et al. (2017) estimated K decreases from more than 60 to less than 10 meters per day from the upper to lower reaches of the basin and were derived from pumping tests carried out in tube wells of generally less than 100 meters deep. Both sets of estimates are consistent with sediment deposition, which grades from sands and gravels in the upper reaches to finer sediments in the lower reaches.

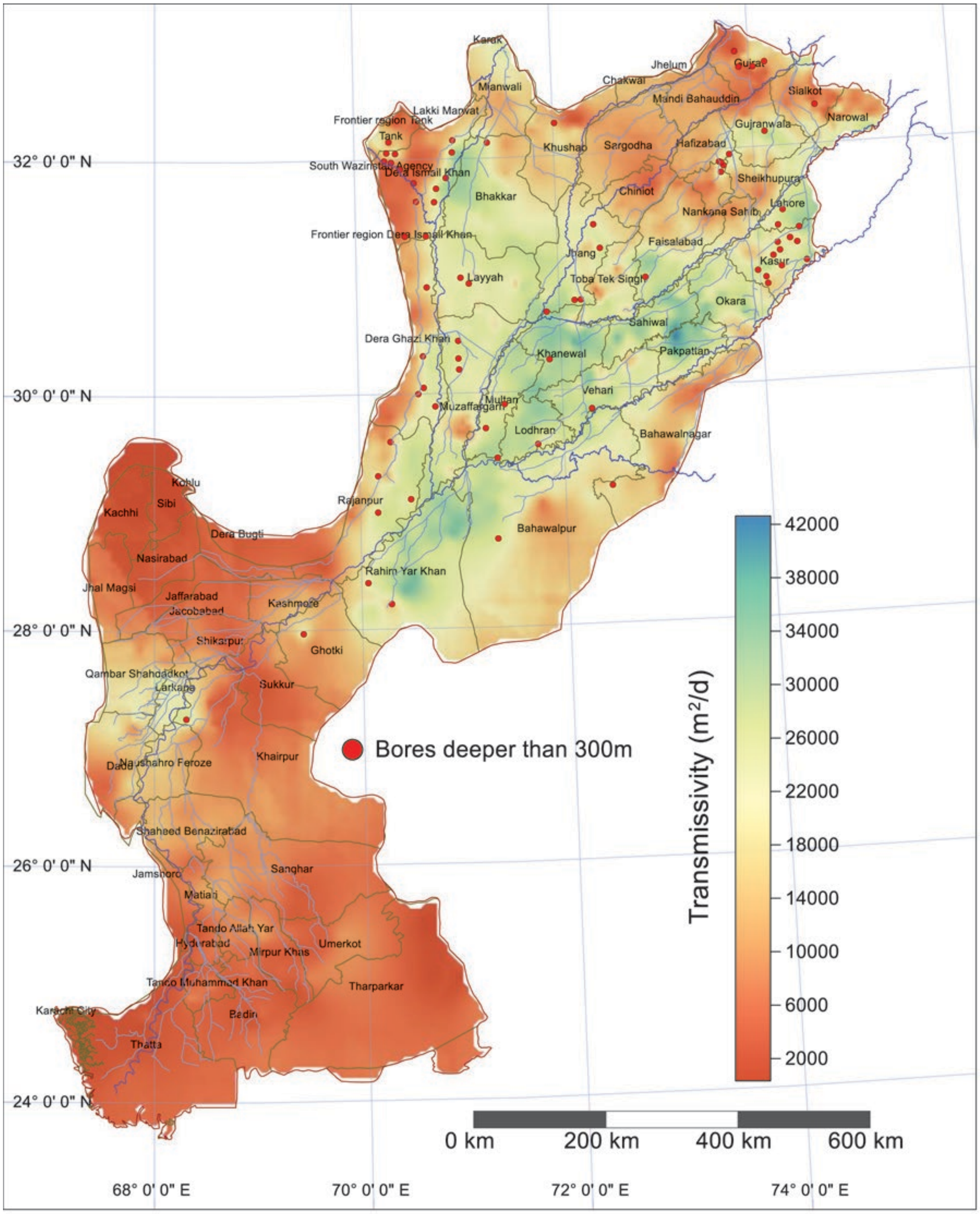
K values are higher in Bari Doab and parts of Rechna Doab than in other parts of the Pakistan Indus basin, shown by the blue and green regions in map 3.4. There is also a zone of high K stretching from east of Kasur near the border with India toward Lahore. There are areas of low K along the eastern border in Bahawalnagar and Bahawalpur districts, in the northwest of Chaj Doab, and in the districts of Tank and South Waziristan in Khyber Pakhtunkhwa. Lower values are also present in the coastal districts of Badin, Tharparkar, and Thatta.[3]

The spatial distribution of specific yield ranges from 0.04 to 0.21 and, as shown in map 3.5, declines by an order of magnitude from the upper reaches of the Indus alluvium toward the delta. It is highest in the piedmont and large megafans, where grain sizes and porosity are high, though overall aquifer thickness is often lower here than elsewhere in the basin (Bonsor et al. 2017). Specific yields for the doabs and in the canal command areas are reasonably high and extend along the left bank of the Indus. Pumping tests in Rechna Doab indicate an average specific yield of 0.14 (ACE, AGC, and SMEC 2011), which is consistent with basin specific yields in the range 0.1 to 0.15 reported by Bonsor et al. (2017). Zones of lower specific yield are generally in the desert regions of Punjab (eastern parts of

MAP 3.2. **Location of Bores Used for Analysis of Aquifer Parameters and the Location of Doabs in the Pakistan Indus Basin**



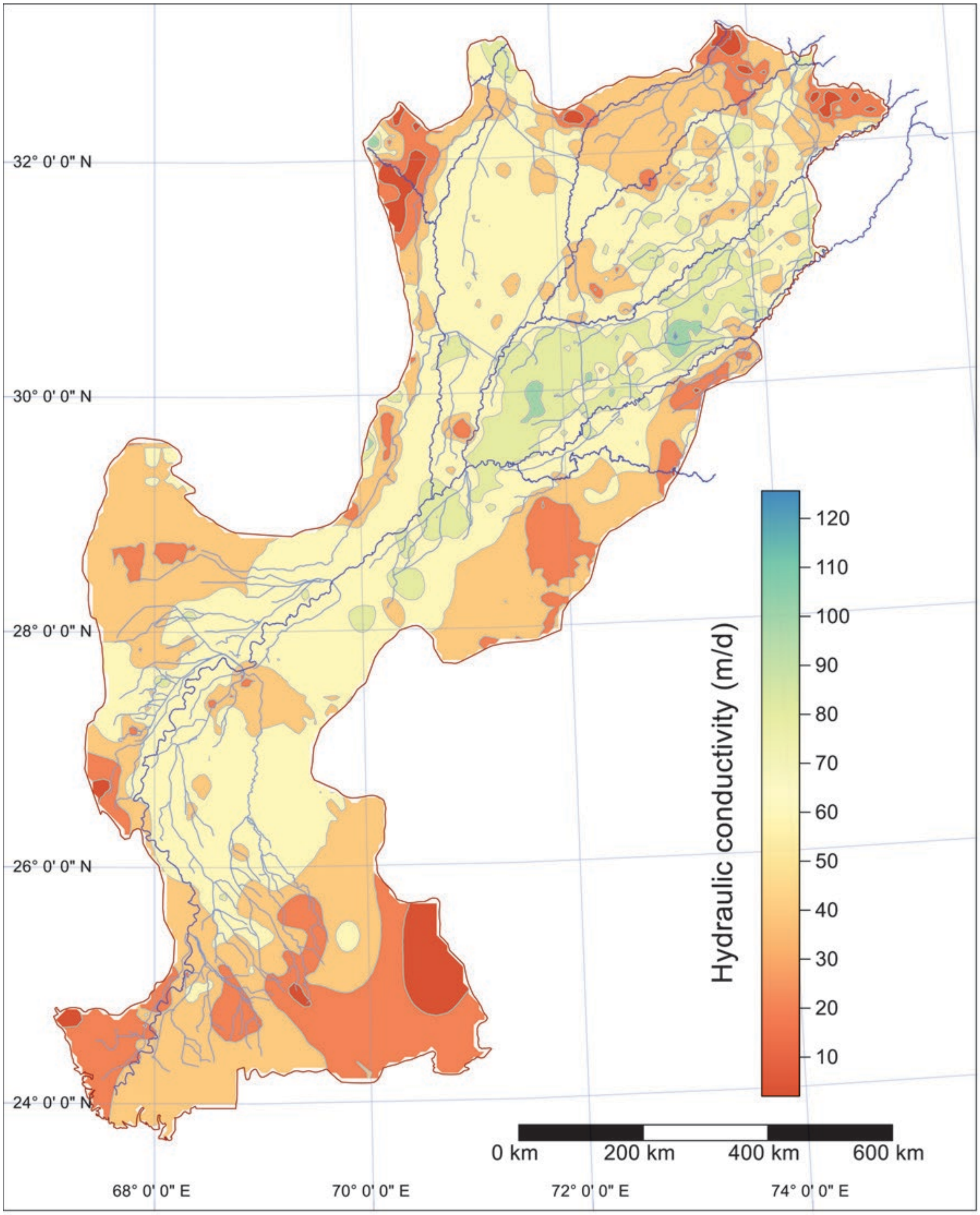
MAP 3.3. Transmissivity of Indus Basin Alluvium



Source: Original compilation.

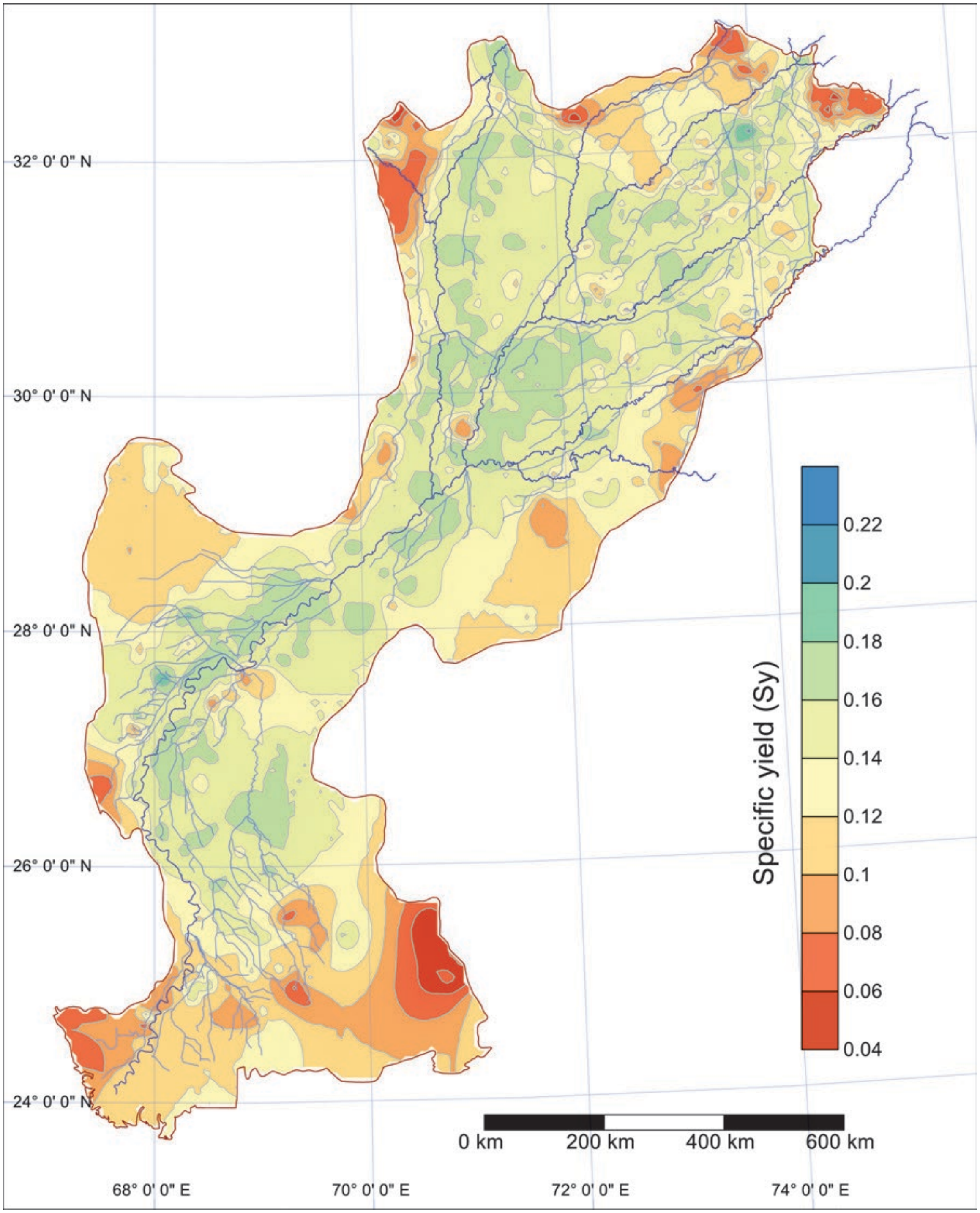
Note: m^2/d = meters squared per day.

MAP 3.4. **Hydraulic Conductivity of Indus Basin Alluvium**



Source: Original compilation.
Note: m/d = meters per day.

MAP 3.5. Specific Yield of Indus Basin Alluvium



Source: Original compilation.

Bahawalpur and Bahawalnagar districts in the Cholistan Desert) and Sindh (Umerkot district and northeastern parts of Tharparkar in the Thar Desert), as well as in the coastal district of Badin in Sindh. In the delta areas, Bonsor et al. (2017) reported specific yields as less than 0.05 because of the increase in silt content, similar to the earlier analysis using borelogs.

Sediment deposition grades from sands and gravels in the upper reaches of the Indus basin to silts and finer sediments in the lower reaches of the basin. The deep freshwater aquifer in Punjab allows the aquifer to be used extensively for irrigation and offers flexibility for management and use of groundwater resources. In Sindh, the diminishing topographic gradient combined with the finer sediments serve to retard groundwater movement, reduce storage capacity, and make waterlogging (and salinity problems) more likely, particularly in the Indus Delta. In Sindh, the freshwater zones are in pockets along the river and main canals, and groundwater extraction needs to be balanced to minimize upconing of deeper saline groundwater.

These factors have implications for groundwater management policy, though significant local heterogeneity exists and management decisions should be based on local measurements rather than broad trends.

Aquifer Cross-Sections

Cross-sections in Punjab and Sindh (map 3.6 and figures 3.1–3.5) illustrate the variations in aquifer topography and the implications for sustainability of groundwater abstraction and water storage. The cross-sections taken here are from different parts of the Indus basin to underscore the variation in alluvium composition, thickness, and permeability across the aquifer. Although the thickness of the alluvial sediments in Punjab is reported to be in excess of 1,000 meters in places (ACE, AGC, and SMEC 2011), the deepest bores available for this assessment were 520 meters deep in Gujranwala district (Punjab) and 409 meters in Khairpur district (Sindh).

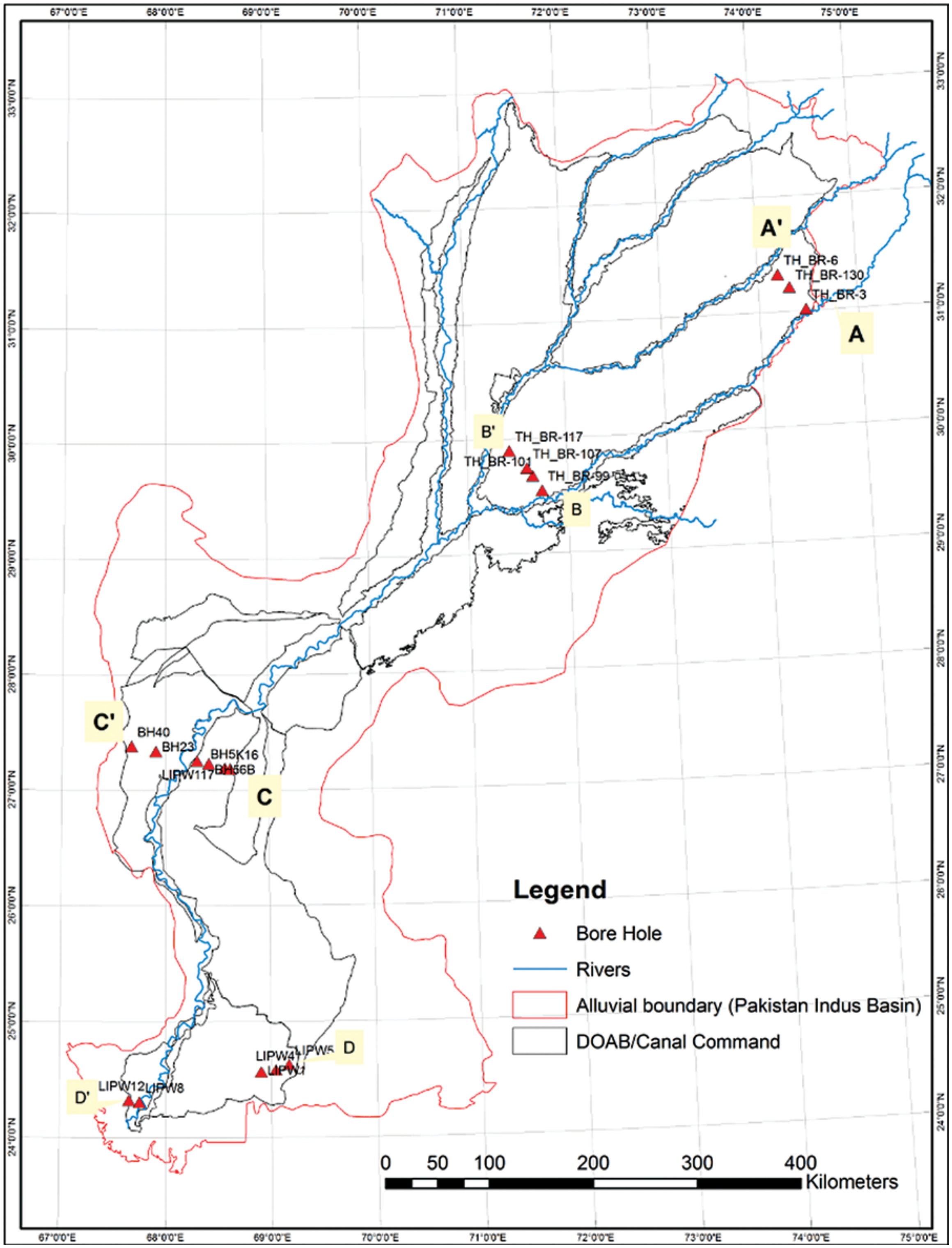
The location of four cross-sections through upper and lower Punjab and Sindh are shown in map 3.6, with detailed stratigraphy at these locations: (a) upper Bari Doab, deep bores between Ravi and Sutlej (Lahore-Kasur Section A’-A, figure 3.1); (b) lower Bari Doab (Multan-Lodhran Section B’-B, figure 3.2); (c) lower Indus through LIPW117, (Larkana-Khairpur Section C’-C, figure 3.3); and (d) Indus coastal districts (Thatta-Badin Section D’-D, figure 3.4).

Further cross-sections in figure 3.5, shown to illustrate the considerable variations in thickness of the aquifer both laterally and longitudinally, correspond loosely to the positions shown on map 3.6 but extend across the width of the basin in Pakistan.

Northern Punjab (Cross-Section A’-A)

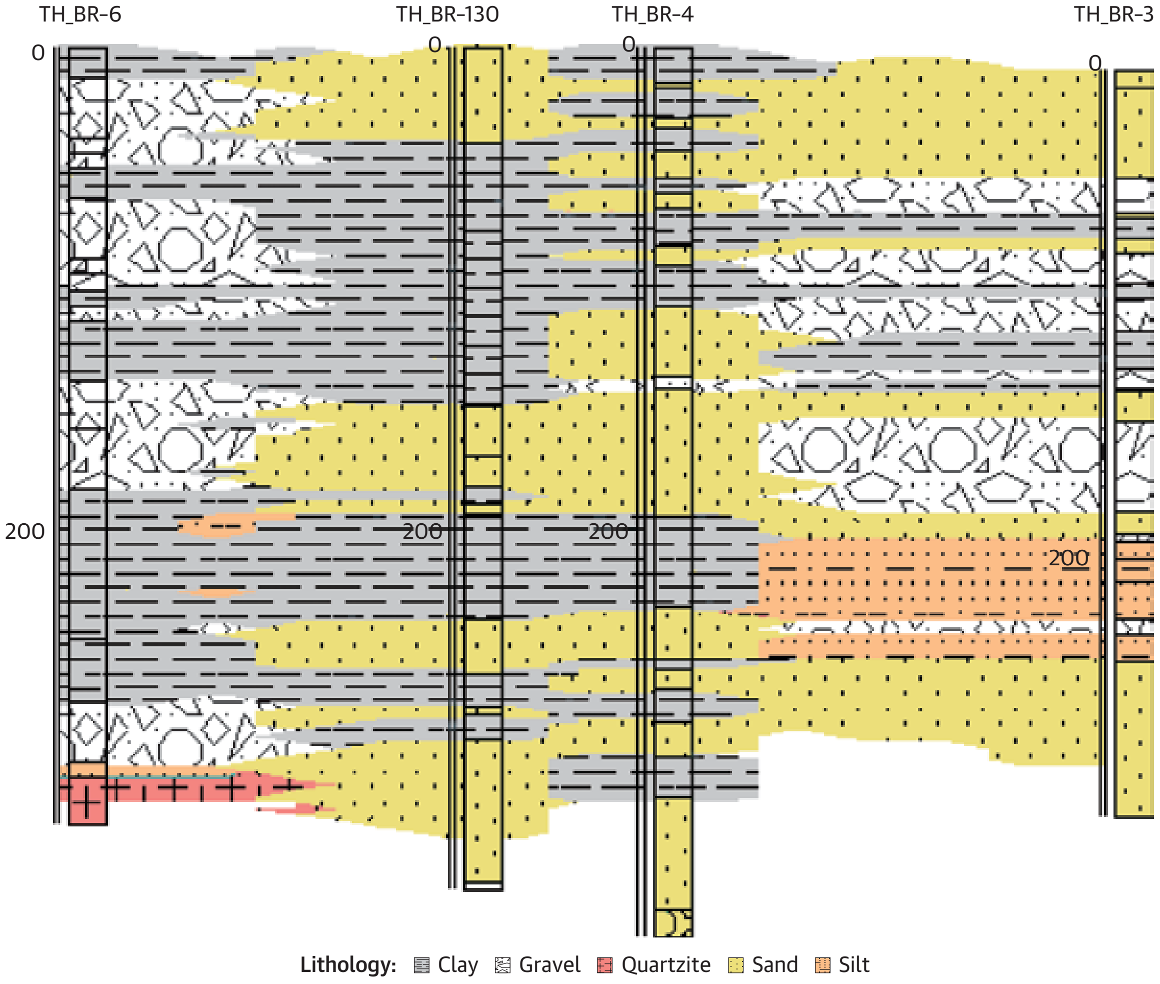
The northernmost cross-section is from the upper reaches of the Bari Doab and cuts across Lahore and Kasur districts (figure 3.1). Four boreholes are used across the two districts to map this cross-section. Bore TH_BR-6 in Lahore has thick sequences of gravel up to 290 meters with clay layers in between. In the mid-regions of upper Bari Doab, alternate sequences of clays and sands are present. In bore

MAP 3.6. Location of Cross-Sections in the Indus Basin through Upper and Lower Sindh



Source: Original compilation.

FIGURE 3.1. Cross-Section A′-A, through the Upper Reaches of Bari Daob, through Lahore and Kasur



Source: Original compilation.

TH_BR-130, a thick sequence of clays is present from about 50 to 150 meters with a sand layer encountered at a depth of more than 240 meters. Where this layer of clay is locally extensive, it will create a two-layer aquifer system with likely confined to semiconfined hydraulic behavior in the lower aquifer. The latter would also be better protected from pollution from activities on the ground surface. The salinity of groundwater in these layers cannot be estimated without location-specific and depth-specific salinity data, although groundwater salinity in the basin is known to increase with depth.

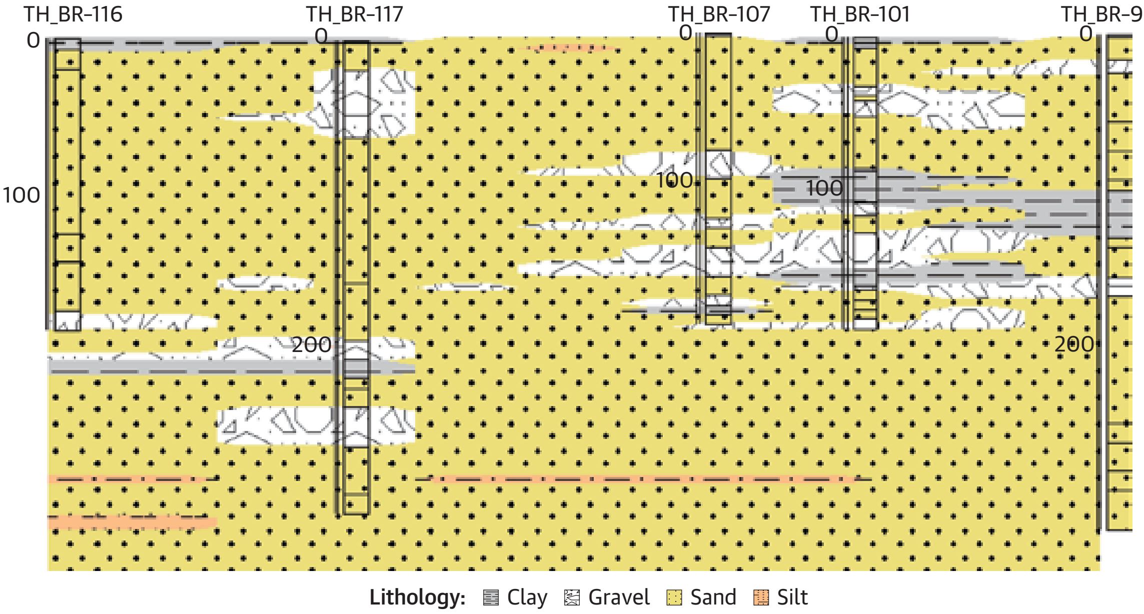
Alternating layers of clay and sand are also present in TH_BR-4 toward the mid-regions of the doab. TH_BR-3 on the eastern edge of Kasur district has mostly sands and gravels up to 200 meters with a layer of silt followed by thick deposits of sand below 250 meters. The sand layer is more than 60 meters thick and extends to a depth of more than 310 meters—the full depth of the bore at which it has yet not encountered the basement. Reasonable quantities of fresh groundwater are available in the top 100 meters, and possibly to greater depths.

The full cross-section for northern Punjab (panel a of figure 3.5) is taken from boreholes that run through the districts of Dera Ismail Khan (Khyber Pakhtunkhwa), Bhakkar, Gujranwala, and Sargodha. These districts lie to the north and west of Lahore and Kasur. Basement depth is based on available bore records. This is an area where the basement structure should be revisited if the influence of the Shahpur Delhi basement ridge (see box 3.1) is to be represented and considered in any future model of the basin's water resources.

Southern Punjab (Cross-Section B′-B)

The cross-section across the lower reaches of Bari Doab through the districts of Multan and Lodhran (figure 3.2) shows part of the basin that has the thickest layer of alluvium. Here the alluvium is composed of a thick layer of sand with minor sequences of gravel, clays, and some silt deposits. The sands are more than 300 meters thick, indicating that the aquifer in this region has good storage potential. The aquifer in this part of the basin is largely unconfined but may be locally semiconfined. It is also highly transmissive and susceptible to surface pollution, including industrial and agricultural pollutants, and municipal waste, where it is disposed directly into drains and rivers. Salinity with depth is not well characterized and may influence the utility, and management, of groundwater in these sediments.

FIGURE 3.2. **Cross-Section B′-B through Lower Reaches of Bari Daob through Multan and Lodhran**

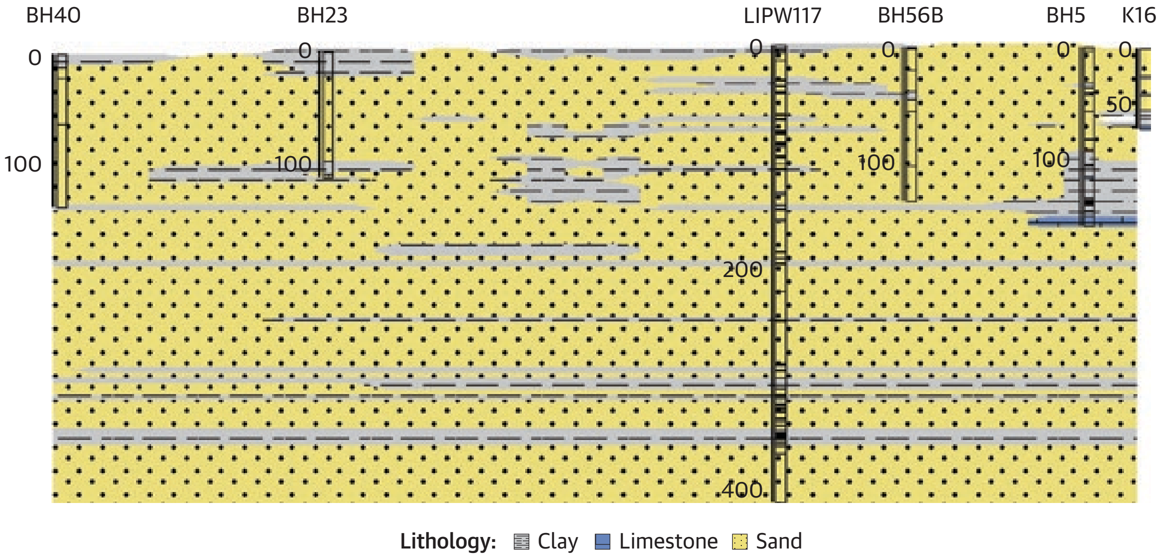


The cross-section that extends through the basin in southern Punjab (panel b of figure 3.5) shows the land surface has a gentle gradient from east to west toward the Chenab River. It goes through the districts of Dera Ghazi Khan, Thal, and Bari doabs and Bahawalnagar district and exhibits a significant depth of alluvium, which is deeper in the vicinity of the Chenab River upstream from its confluence with the Sutlej River. In parts, the alluvium may be much deeper than indicated, especially in the vicinity of major rivers.

Mid-Regions of Sindh (Cross-Section C′-C)

The cross-section through the lower Indus plain through Qambar Shahdadkot, Larkana and Khairpur districts in the mid-region of Sindh is given in figure 3.3. This cross-section includes the deepest drilled bore in Sindh (LIPW117), extending to a depth of 409 meters in Khairpur district and ending in alternating layers of sand and clay, which suggests the base of the aquifer is even deeper at this point. Many of the bores in Sindh are not as deep as the bores in the doabs in Punjab because of increasing salinity with depth. The sand deposits in this cross-section are relatively thick and interbedded with thin layers of clay and with shale layers at about 300 and 350 meters. Much of the freshwater exploitation in Sindh occurs between 30 and 60 meters.[4] Fresh groundwater is found in pockets that are aerially extensive between the left bank of the Indus River and Rohri Canal, where river recharge and canal seepage has accumulated. The groundwater increases in salinity with depth, which requires careful management of extraction to avoid upconing and lateral saline water intrusion. Tube wells supply groundwater for irrigation, which is used conjunctively with surface water.

FIGURE 3.3. Cross-Section C′-C through Lower Indus in Qambar Shahdadkot, Larkana, and Khairpur Districts, Sindh



The cross-section across the basin (panel c of figure 3.5) through Larkana on the right bank and Khairpur and Sukkur districts on the left bank of the Indus was selected to show the basement high in Khairpur because of the outcrop of the Kirthar Hills. The surface topography also shows the prominent outcrop area (the Kirthar Hills) in Khairpur district. The deepest bore in Sindh (LIPW117) is also in this area and shows the deep alluvium in the vicinity of the Indus River. Between the river and the outcrop, a freshwater lens is present, which is exploited for groundwater irrigation. East of the outcrop, there is no groundwater irrigation as salinity of the groundwater increases in this region (and this area is outside the canal command areas); however, there is limited irrigation along the banks of Nara Canal, which is evidence of a lens of fresh seepage water resting on the saline groundwater.

Coastal Regions of Sindh (Cross-Section D′-D)

A cross-section through the coastal regions of Sindh through Thatta and Badin districts (figure 3.4) shows a greater presence of clays compared to previous cross-sections. Here there are some sand sequences of a few meters to about 50 meters interlayered with clays. The bores in this cross-section are drilled to depths ranging from 92 to 135 meters. It is likely that the alluvium is much deeper and a similar complex of sands and clays are present at greater depths.

The cross-section across the full width of the basin (panel d of figure 3.5) includes Tharparkar district and shows that the base of the alluvial aquifer is considerably deeper there, extending up to 300 meters (Mueller et al. 1991). The true thickness of the alluvium in the Thatta and Badin areas is not known because of the absence of deep boreholes—drilling would have stopped once saline groundwater was encountered (at 10 to 30 meters). Additionally, the surface topography in the eastern area in Tharparkar is about 100 meters higher compared with the surface elevation in coastal Thatta and Badin districts. As a result, there is very little groundwater use there other than hand pumps and a few bores tapping pockets of freshwater. However, even in this area, some farmers use innovative methods for tapping the freshwater lens, which essentially relies on the transmissive nature of the aquifer and seepage from irrigation return flows. In the long run, this is probably not sustainable as salinity will increase. Parts of this region have thick clay sequences near the surface that overlie deeper water-bearing sand layers and are likely to provide protection from pollutants. However, as saline groundwater is found even at shallow depths, the groundwater in these layers is likely to be highly saline. In line with the identified

FIGURE 3.4. Cross-Section D′-D through Lower Indus in Coastal Districts of Thatta and Badin, Sindh

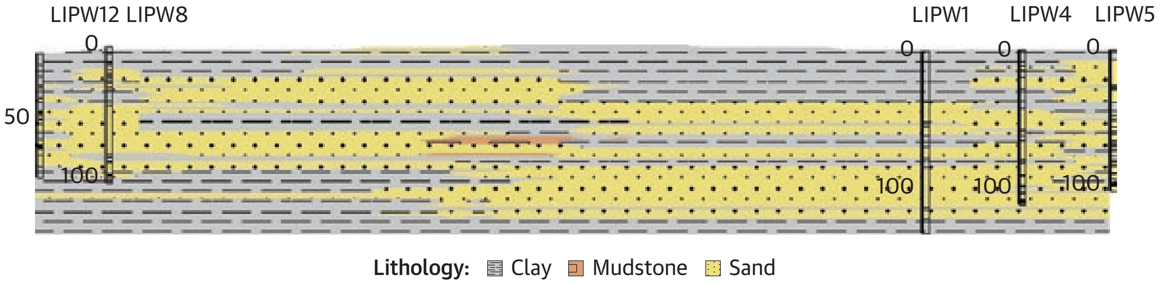
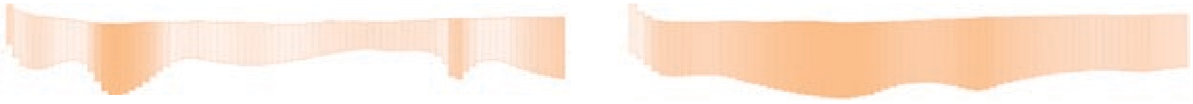
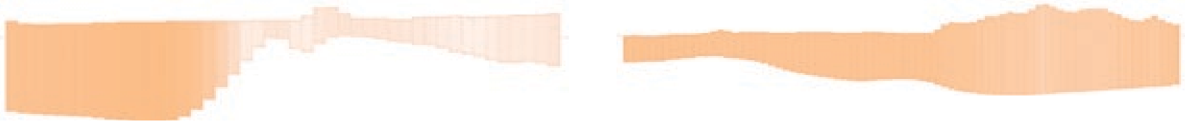


FIGURE 3.5. West to East Cross-Sections Showing Variation in Aquifer Thickness



a. Punjab – Dera Ismail Khan (KP), Thal, Chaj, Rechna, and Bari doabs, Punjab

b. South Punjab – Dera Ghazi Khan, Thal, and Bari doabs and Bahawalnagar district



c. Sindh – Qambar Shadadkot, Larkana, Khairpur, and Sukkur districts

d. Coastal Sindh – Thatta, Badin, and Tharparkar districts

hydraulic properties in this part of the basin (section 3.2.1), aquifer yields are poor and groundwater is susceptible to seawater intrusion and upconing.

The heterogeneous distribution of sediments demonstrated in the local cross-sections, and the variation in aquifer thickness, are important considerations for monitoring and managing the groundwater resource and determining the scale of interventions.

Water Level and Salinity Trends in the Indus Basin

Water level and salinity measurements made frequently at several locations are essential in understanding seasonal groundwater system response and in evaluating the extent and risk of waterlogging and salinity. Depth to water table and salinity data from two sources are used in this report: the Directorate of Land Reclamation (DLR) bores provided by the Punjab Irrigation Department for mapping temporal patterns and the Salinity Control and Land Reclamation Project (SCARP) Monitoring Organization (SMO) bores for mapping spatial patterns. Salinity measurements are from water samples taken from tube wells. Borehole data were supplemented with a Pakistan Council of Research in Water Resources (PCRWR) study on groundwater investigations and mapping in the upper Indus plain (Khan et al. 2016) and personal communication with key stakeholders involved in groundwater monitoring.

Several limitations were observed in the data sets, indicating an absence of data and monitoring protocols. Most commonly, these included coordinate errors, inconsistencies in units used, duplication of bore names across different doabs, missing readings because of bore failure or abandonment, missing locations and reference elevations, and reading errors on account of manual readings. In the case of DLR bores, it was observed that they are physically located in secure locations, such as public schools, as opposed to agricultural fields where the bulk of groundwater abstraction takes place. Secondly, the water level readings are only recorded semiannually—pre- and post-monsoon season—providing insufficient resolution. Thirdly, there is no unique numbering system for DLR bores, and differentiation of bores is based on locational information. Coordinates are not given for all bores, and the names of nearby villages are used to approximate coordinates. The previous section of this report demonstrates the considerable variability that exists in the sedimentary layering within the Indus basin and the effect this variability can have on hydraulic response and aquifer vulnerability. Having inaccurate locations for groundwater monitoring bores impairs the ability to match hydraulic behavior to the strata and thus limits understanding of the resource and the application of a sound approach to managing it.

Out of the 3,000 DLR bores that exist in Punjab, only about 1,700 are thought to be functional. In the case of SMO bores, complete data sets are available only for selected periods. After selecting only those bores for which both pre- and post-monsoon readings were taken, only two-thirds of the data points remained. SMO bore data also suffered from some of same deficiencies and inconsistencies observed in the DLR bore data. Hence, the existing data from both the sources need rigorous checking to correct errors and a consistent approach for how to address missing data points and information. The analysis is meant to outline the broad temporal and spatial patterns in different locations across the Indus basin and to illustrate the significance of water level and salinity monitoring. Some of the findings seem inconsistent with broadly reported patterns of pumping and groundwater use, but it is difficult to provide definitive explanations in the absence of robust (reliable, frequent, complete) and accessible data.

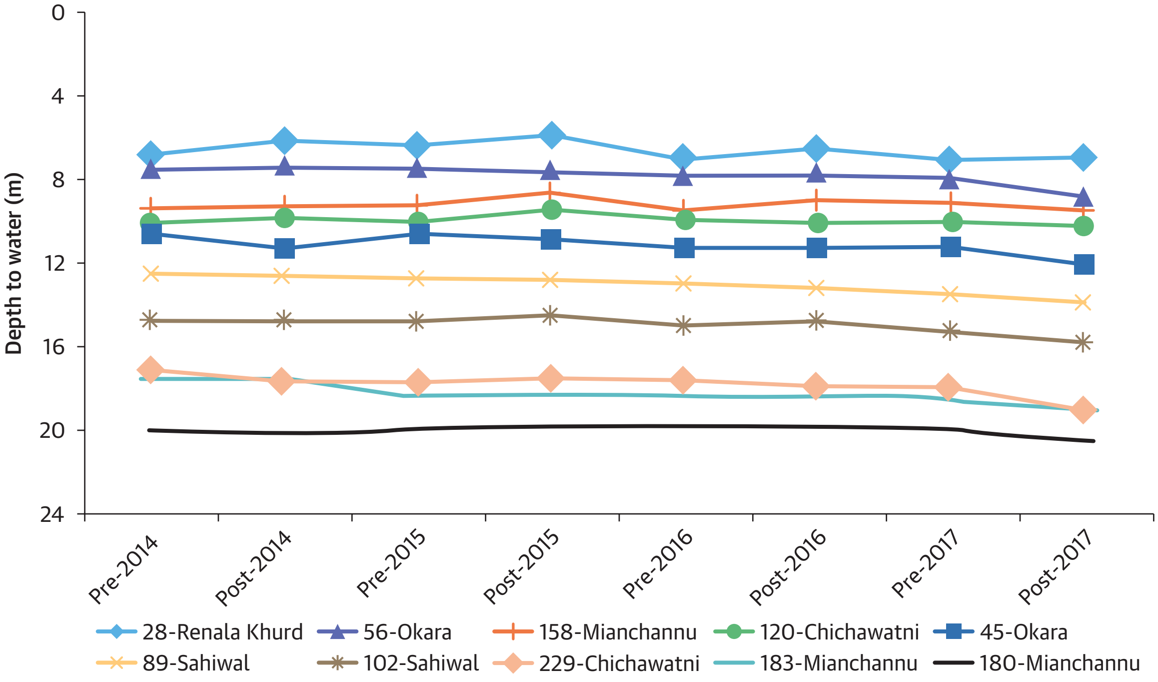
Temporal Water Level and Salinity Trends

The depth to water table in Bari Doab is shown in figure 3.6 for selected DLR bores, which are located from north to south in the districts of Okara, Sahiwal, and Khanewal in Punjab. Water-level data show a gradual decline in only some of the bores between 2014 and 2017, despite high levels of pumping. Locally some bores may exhibit steeper declines as observed in bore 183 (Mian Channu) and bore 229 (Chichawatni). The timing and location of readings, and the short length of recorded readings (2014–17), could explain this pattern. A more sophisticated analysis of data trends is not meaningful for a data set containing only two measurements a year and without more precise date information that would support linkages with other data sets (such as rainfall and evapotranspiration).

Of the few long-term groundwater data sets, groundwater levels from two bores in the lower Bari Doab in Khanewal and Sahiwal districts show a gradual decline since the high levels of the 1980s (see figure 3.7). In the Sahiwal division, the decline in groundwater levels averages about 0.18 meters per year, whereas in the southernmost division (Khanewal), the decline averages 0.34 meters per year (Basharat and Tariq 2015). These declines are resulting in increased pumping costs for farmers and reduced water quality as freshwater lenses are depleted (Basharat and Tariq 2015). Comparison of the two trends provides an eloquent demonstration of the value of reliable long-term data as a basis for planning and groundwater resource management.

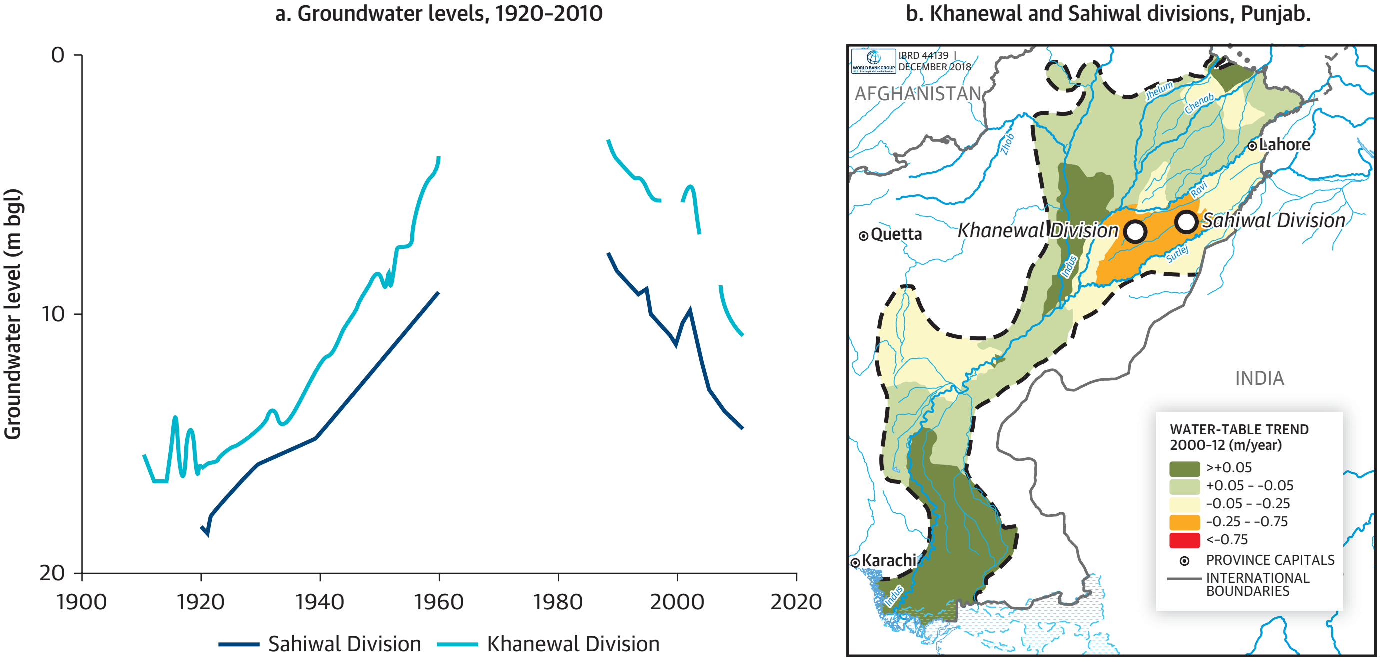
The depth to water table for DLR bores in Ahmad Pur Sial Tehsil in Jhang district in the Multan irrigation zone of south Punjab (figure 3.8) shows water levels are generally steady between 2003 and 2009; however, there is a noticeable increase in depth to water pre-monsoon and commensurate recovery for the post-monsoon water levels.

FIGURE 3.6. Depth to Water Table for DLR Bores in Bari Doab



Source: Original compilation, using data from the Government of Punjab.
Note: DLR = Directorate of Land Reclamation; m = meter.

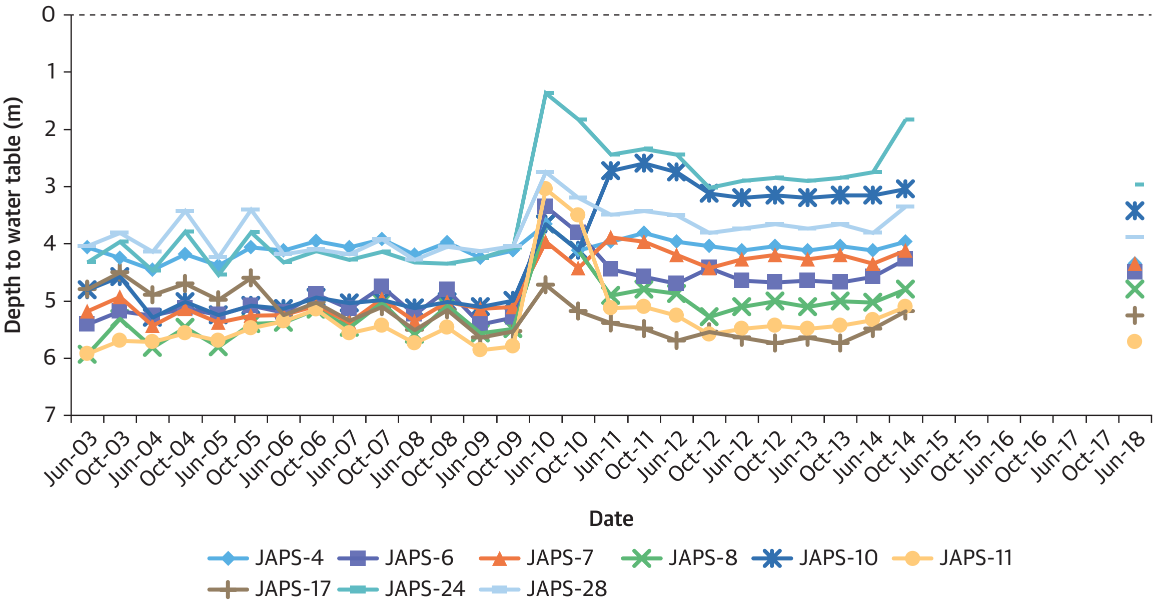
FIGURE 3.7. Groundwater Levels in the Khanewal and Sahiwal Divisions, Punjab, 1910–2010


a. Groundwater levels, 1920–2010

b. Khanewal and Sahiwal divisions, Punjab.

Source: Alan McDonald, British Geological Survey, *personal communication.* As reprinted in Young et al. (2019).

FIGURE 3.8. **Depth to Water Table for DLR Bores in Ahmad Pur Sial, Jhang District**



Source: Original compilation, using data from the Government of Punjab.

In 2010, water tables showed a sharp increase, a trend common to all bores in Ahmad Pur Sial. This sudden increase is interpreted as a result of the floods experienced in Pakistan in July 2010 but recorded as June 2010 (before the floods) because the data recording system is arbitrarily set up to store water levels only in June and October (nominally pre- and post-monsoon), irrespective of when the measurements are actually made (and the actual date of each measurement is not recorded). This single flooding event raised water tables by more than 2 meters in some bores, and water tables remained between 0.2 and 0.5 meters higher after the flood, indicating the potential of the aquifer for storing additional water during the monsoon. The ability to understand the responsiveness of the groundwater system to specific events is hampered by the inaccuracy of the dates associated with each measurement. Declining water tables and increasing water demand in the major cities of Punjab is increasing pumping costs and depleting aquifers. Amir and Habib (2015) refer to the fall in the water table due to excessive pumping in urban centres which now face a risk of forced out-migration due to lack of water or deteriorating water quality. Trends in Lahore, Multan, Faisalabad, and Sheikhupura exhibit a gradual and steady decline in water tables (figure 3.9) and a muted seasonal trend in some bores. As these are located in urban areas, they reflect that demand will be fairly constant and rainfall recharge is likely to be restricted. Although there is public anxiety that groundwater from some of these locations is also extracted by commercial bottled water plants (*Dawn* 2018), there are no available data that indicate this activity is causing local depletion more than that caused by other nearby extractions (public or private, industrial or domestic).

Urban areas present particular problems, including concentrated pollution and overabstraction. For example, the aquifer in the city of Lahore is a single contiguous, unconfined aquifer that supplies water for drinking, domestic, commercial, and industrial purposes. Within Lahore, there are 500 publicly owned tube wells and 100 private tube wells (Young et al. 2019). Groundwater is extracted from depths of between 120 and 200 meters, and extraction exceeds aquifer recharge. This has resulted in an expanding cone of depression under the city of more than 38 meters (by 2011), as indicated in figure 3.10. The average annual depletion rate increased from 0.3 meters per year in the 1960s to more than 0.7 meters per year by the late 2000s (Mahmood et al. 2013). This decline in groundwater levels means an

FIGURE 3.9. **Depth to Water Table in Lahore, Multan, Faisalabad, and Sheikhupura**

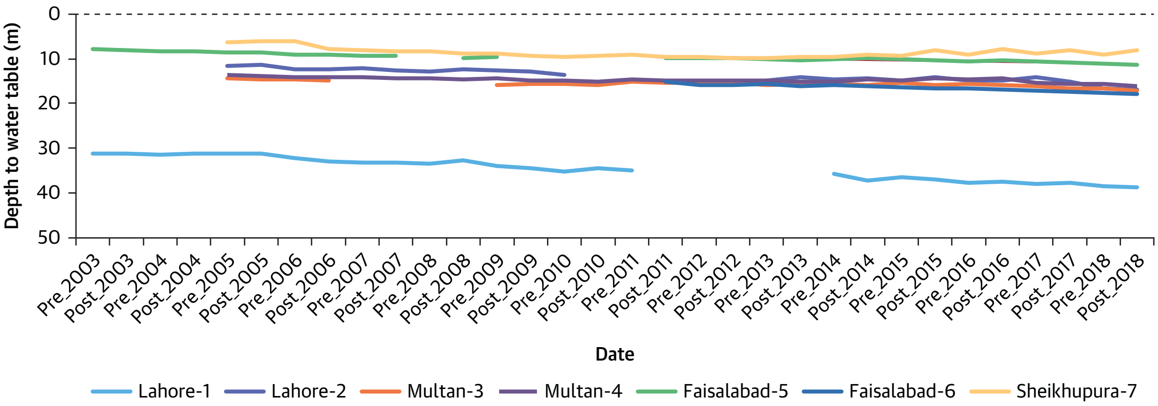
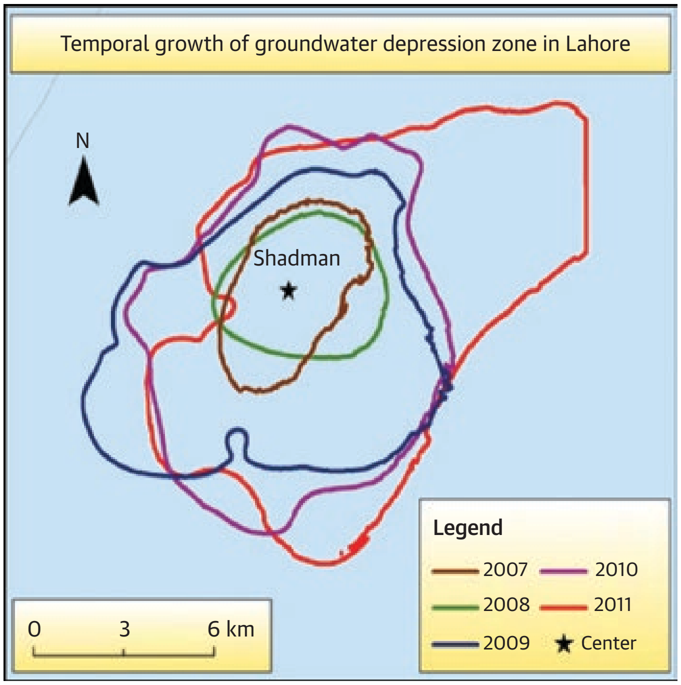


FIGURE 3.10. **Expansion of the Cone of Depression for the 38-M Drawdown Contour in Lahore from 2007-11**

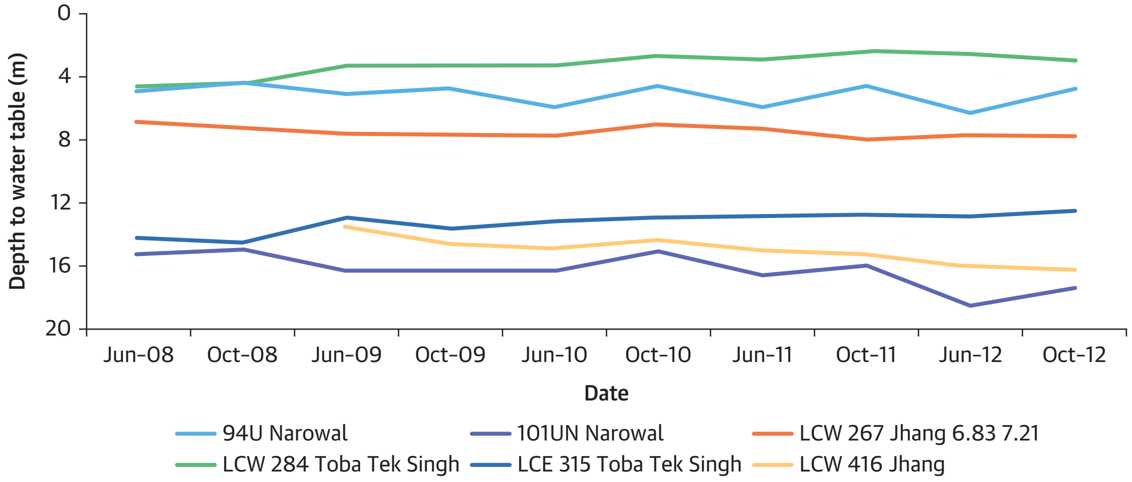


Source: Mahmood et al. 2013.

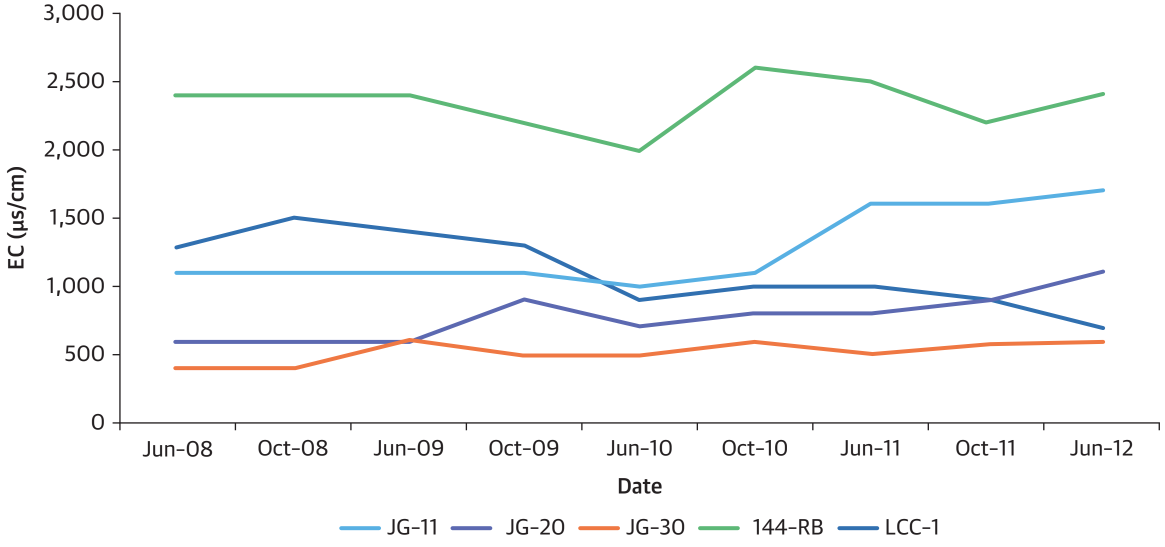
increasing loss of groundwater in aquifer storage, a decline in the quality of groundwater (Qureshi and Sayed 2014), increased pumping costs for the water and sanitation agency (WASA), and ultimately higher water charges for users. The inaccuracy of groundwater data, the infrequency of measurement, and the lack of withdrawal measurements combine to hamper a clear understanding of how the groundwater system is affected by individual activities.

In Rechna Doab, the water level in most of the bores appears stable between 2008 and 2012. This understanding may be an artifact of the short period for which data were available (figure 3.11).

FIGURE 3.11. Depth to Water Table and Electrical Conductivity for DLR Bores in Rechna Doab



a. Depth to water table



b. Electrical conductivity

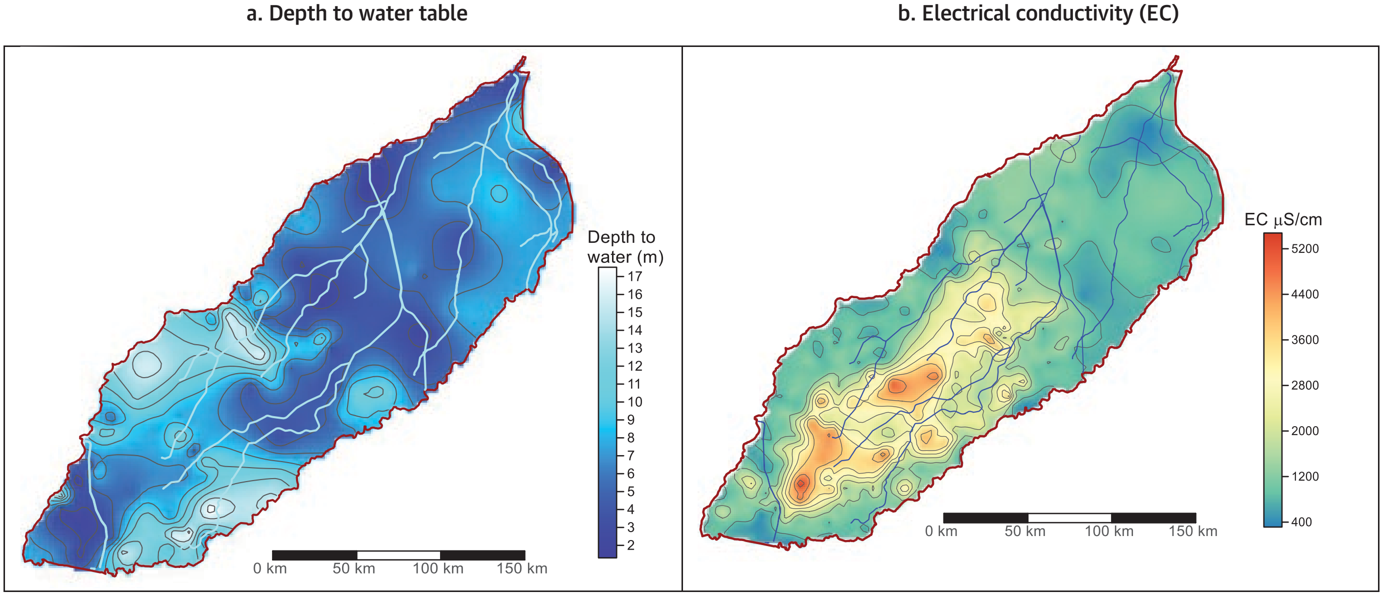
Note: DLR = Directorate of Land Reclamation; EC = electrical conductivity; m = meters; µS/cm = microsiemens per centimeter.

A few bores in upper regions of the doab show a small rising trend from 2008 to 2012, whereas bores in lower regions of the doab show a slight declining trend. However, bore LCE315 in Toba Tek Singh, which is in the lower reaches of the doab, shows a slight rising trend that is likely a result of its proximity to Burala Branch Canal and seepage from the canal (panel a of figure 3.11). All the bores show a rise in water table in 2010 (post-monsoon), which coincides with the widespread flooding in late July 2010. Analysis of the data shows many bores are not in use or recording from these bores has been abandoned as a result of bore failure. Moreover, several possible recording errors were observed in the water-level data, probably because of manual recording of water levels or even the occasional use of estimates.

Water tables tend to be deeper in the lower regions of Rechna Doab. In panel a of figure 3.12, water tables are deeper (greater than 17 meters) in the southern part of Chenab district and near the lower reaches of Ravi River. This may be because of pumping being concentrated near tail ends of Lower Jhang, lower Gugera, and Burala branch canals and reduced flows in the Ravi River. There are localized areas in the Rechna Doab where overpumping is occurring, and the infrequent monitoring of water levels and salinity impede an adequate understanding of the state of groundwater resources in Punjab.

Groundwater salinity measured in tube wells in the Rechna Doab is shown as generally stable; however, seasonal fluctuations are discernible. Bores located near the mid-regions of the doab tend to have higher electrical conductivity (EC)[5] values, and slight increasing trends may be occurring depending on the level of pumping at that location. Because only two measurement points are available per year for five and a half years, trends are unclear. The lower mid-portion of the doab tends to have higher salinities (see panel b of figure 3.12). The Upper Chenab Canal Circle, which covers the upper parts of the doab,

FIGURE 3.12. Depth to Water Table and Electrical Conductivity in Rechna Doab, June 2008



Note: EC = electrical conductivity; m = meters; µS/cm = microsiemens per centimeter.

tends to have better-quality groundwater and some bores in the upper doab show a slight decrease in salinity. In the lower parts of the doab (the tail end), salinity shows a rising trend, which may be because of pumping and higher salinity in return flows. Lateral saltwater intrusion and/or upconing of the saline interface is dependent on location and the intensity of groundwater pumping.

A further analysis of salinity trends in the Indus basin is presented in the following section.

Spatial Water Level and Salinity Trends

The network of SMO bores used for mapping the depth to water table and EC are located in the canal command areas (see map 3.7). The density of monitoring bores is higher in Rechna and Chaj doabs, in the southern reaches of Thal Doab in Punjab, and in the Rohri Canal command in Sindh. As indicated earlier, complete data sets, composed of annual pre- and post-monsoon measurements, are available only for a small subset of these bores and for only a few measurement periods.

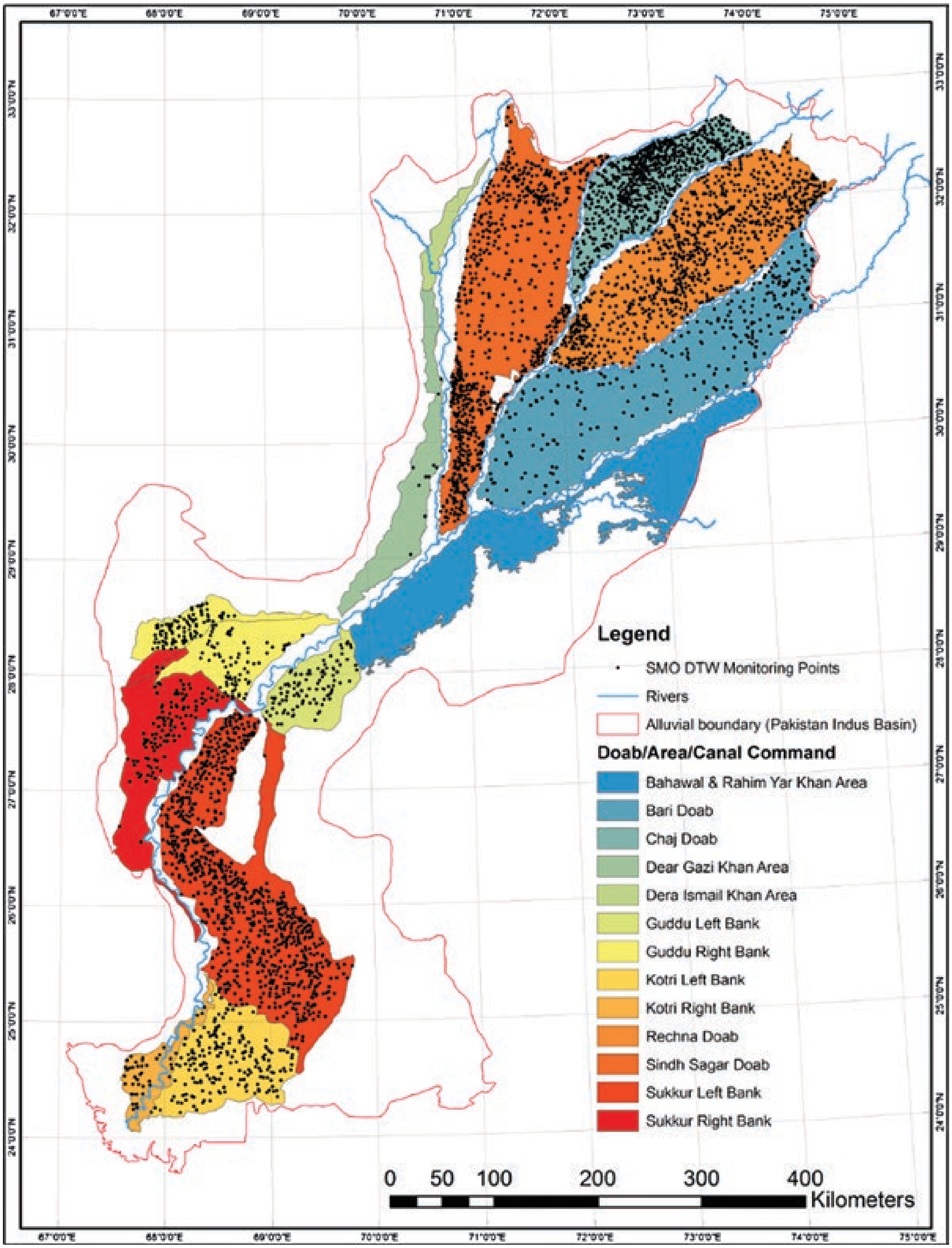
The most complete data set available has been used for mapping water table depth and EC, measured during the pre-monsoon period, nominally June 2014, and for the post-monsoon period, nominally October 2014 (map 3.8), to show as clear a picture as possible of the spatial variation in each parameter for two points in time aimed at showing groundwater conditions at the driest and wettest parts of the year.

Pre- and post-monsoon water tables in 2014 in Punjab are similar to each other. Although there are discrete areas of depletion, such as around the city of Lahore, map 3.8 shows a large and continuous area of depletion in the southeast of the province. The approximate area of this southeast zone of depletion, based on the June 2014 water level contours, is 28,000 square kilometers. The sum of all the shown zones of depletion is 31,055 square kilometers.

In Sindh, water table depths in the post-monsoon period are within 2 meters of the surface (panel c of map 3.8), implying that unusually high rainfall in Sindh during monsoon season will exacerbate waterlogging and may lead to flooding, simply because there is no space for the additional water. This map also shows that the area between Rohri Canal and the outcrops hills in Khairpur are waterlogged following the monsoon. Diverting some of this excess floodwater for lakes and for the delta areas of Sindh would improve environmental outcomes (see chapter 5). The approximate area of post-monsoon waterlogging, based on the October 2014 water level contours, is 56,600 square kilometers, of which the majority lies within Sindh.

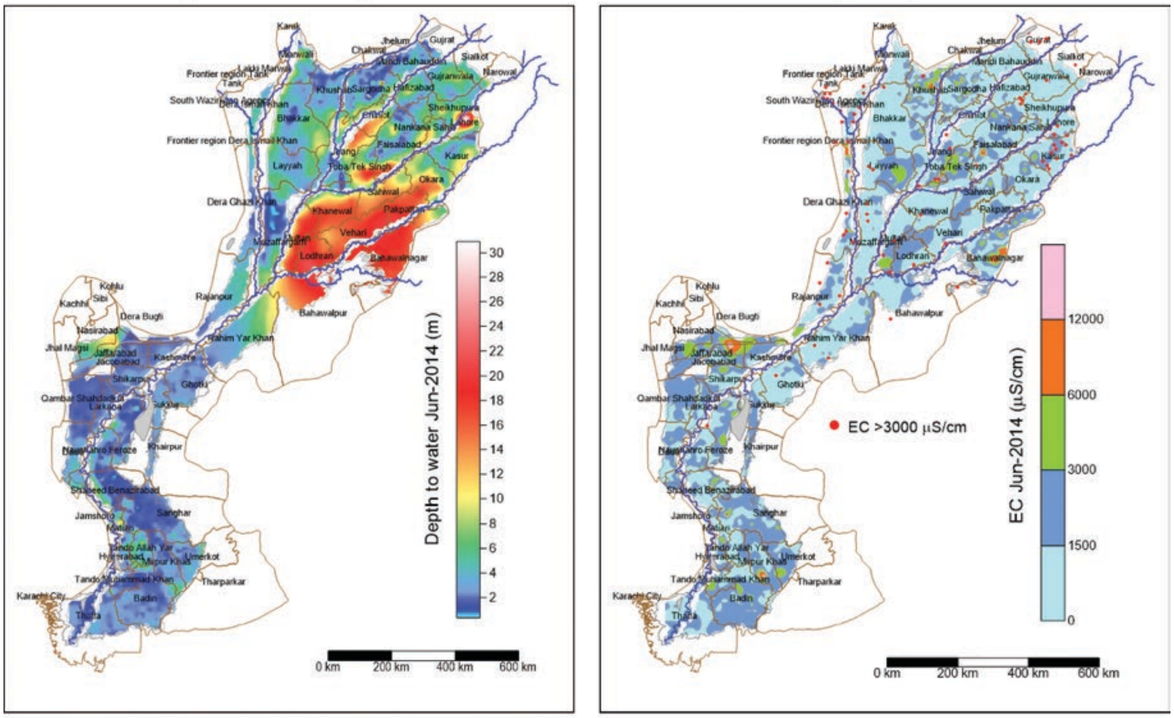
The PCRWR study on groundwater in the upper Indus plain (Khan et al. 2016) indicated the presence of fresh groundwater in Thal Doab and recommends it be used to irrigate an additional 0.7 million hectares of land there. That area has been recharged from the Jhelum and Indus rivers traditionally and from limited rainfall. However, the construction of Thal Canal may have accelerated recharge in the Bhakkar area and the construction of the greater Thal Canal toward the center of Thal Doab. The recommendation by PCRWR will inevitably lead to declining water tables and increasing risk of salinization of the groundwater in this region unless effective regulatory mechanisms are introduced prior.

MAP 3.7. Distribution of SMO Bores for Mapping Depth to Water Table and EC



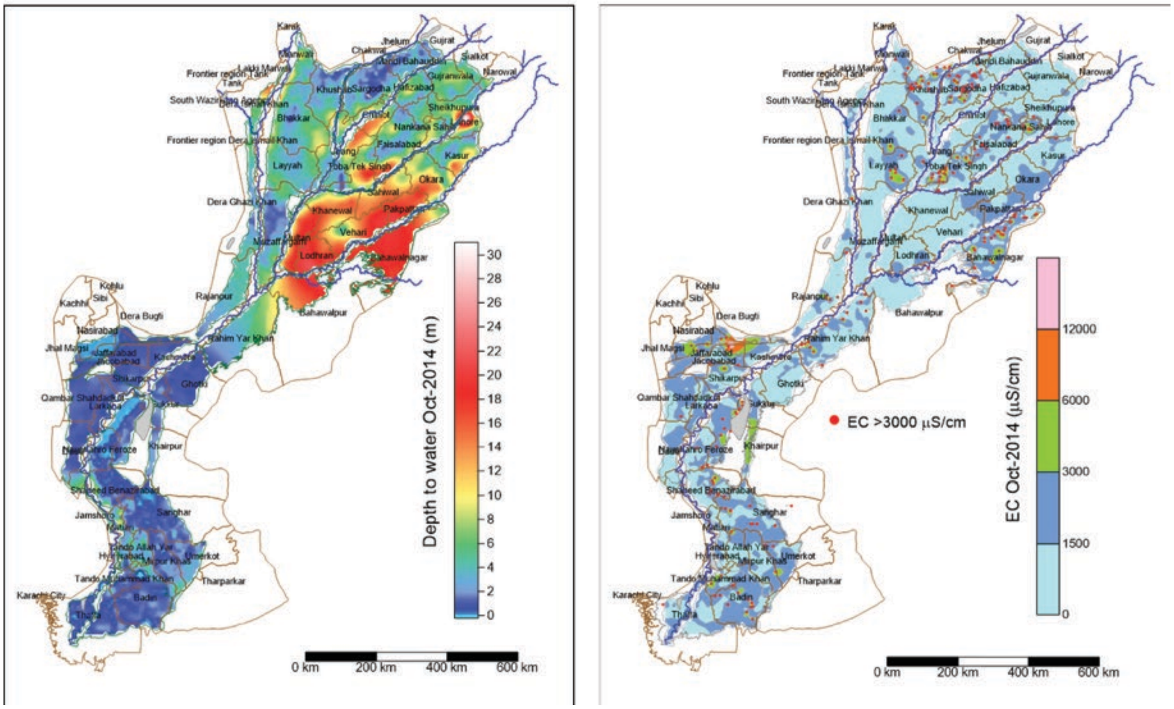
Source: Original compilation.
Note: EC = electrical conductivity; SMO = SCARP Monitoring Organization.

MAP 3.8. Water Table Depth and Groundwater Salinity



a. Depth to water table, Jun 2014

b. Salinity as EC, Jun 2014



c. Depth to water table, Oct 2014

d. Salinity as EC, Oct 2014

Source: Original compilation.

Note: The poor reliability of the underlying data means that both the depth to water and the EC maps must be interpreted with caution.

EC = electrical conductivity; m = meters; µS/cm = microsiemens per centimeter.

Data from bores with EC of more than 3,000 microsiemens per centimeter (approximately equivalent to total dissolved solids [TDS] of more than 1,900 milligrams per liter) (see panels b and d of map 3.8) contribute to the mapping of potential salinity hotspots. In Punjab, these include several bores with EC of more than 3,000 microsiemens per centimeter north of Khushab district and in Sargodha near the Kirana Hills, which outcrop south of Sargodha and tend to be in the mid-portion of Chaj Doab. There is a cluster of high EC bores stretching from Nankana Sahib toward Toba Tek Singh in the southern end of Rechna Doab, along the mid-portions of the doab. High EC values are also present in a line south of the Sutlej River in Bahawalnagar district. With flows cut off in the Sutlej River coming from India, this area is at increasing risk of salinization. The maps show some freshening post-monsoon in the Bahawalnagar region.

Farther south in Sindh, groundwater flows are from the Indus River toward the desert areas to the southeast on the left bank and toward the Kirthar Hills on the right bank. High EC values are found along the left bank of Rohri Canal, along the western edge of the Kirthar Hills outcrop in Khairpur district, and in localized scattered hotspots down to the coastal district of Badin. The eastern parts of Khairpur and Sanghar districts have EC of more than 3,000 microsiemens per centimeter. Very high EC (more than 6,000 microsiemens per centimeter or more than 3,800 milligrams per liter) is found in districts Jacobabad in Sindh and Jafarabad in Balochistan and stretched into Dera Bugti in Balochistan along the western alluvial margin of the basin. The districts of Sibi, Nasirabad, Jhal Magsi, and Kacchi show EC values between 1,500 and 3,000 microsiemens per centimeter (or between 960 and 1,920 milligrams per liter).

Groundwater salinity can exceed 4,600 microsiemens per centimeter (3,000 milligrams per liter) in the Kacchi plain, Jhal Magsi, and Nasirabad. Farmers in these areas do not use groundwater for agriculture purpose because the water quality is not very promising.[6] Areas in the delta regions on both sides of the Indus River show EC values as high as 3,000 microsiemens per centimeter (1,920 milligrams per liter) both pre- and post-monsoon; however, it should be noted that this is for the shallow groundwater and here salinity increases rapidly with depth.

The impact of monsoonal recharge of groundwater is significant. In the post-monsoon period, water tables in Sindh can rise by 1 meter, increasing the risk of waterlogging and salinization. In Punjab, the average post-monsoon water table rise is about 0.5 meters, a concern for the 20 percent of the province with shallow groundwater. Seasonal changes in water levels and salinity highlight the value of regular and accurate monitoring and sampling.

Groundwater and Salt Balance in the Indus Basin

There is no definitive assessment of the water balance of the Indus basin based on basin scale modeling studies. Similarly, because of the lack of high-quality spatial and temporal data from boreholes (explained in the previous section), the salt balance can be only roughly approximated. However, the available data and derived depth to water table and EC maps, coupled with insights from other reports, allow us to estimate groundwater and salt balances in the Indus basin and make deductions about the usable groundwater storage in Punjab and Sindh. These estimates and deductions can be improved further with better monitoring of water levels and EC and by developing a basin scale model of the Indus basin.

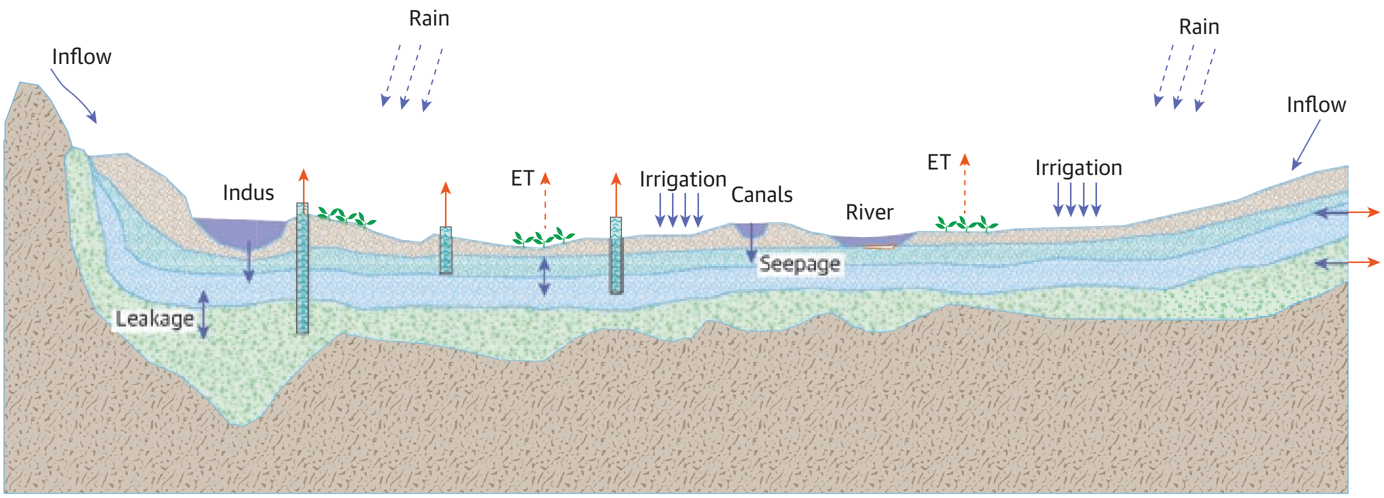
A conceptual cross-section of the Indus basin alluvium in figure 3.13 shows the main stresses on the groundwater system. The conceptual model shows the major inflows are from canal seepage, irrigation return flows, rainfall recharge, and seepage from rivers. There are also boundary flows, such as inflows from the highland areas at the basin margin and groundwater inflow/outflows across the eastern boundary with India. The major outflows are river outflows, evapotranspiration, and groundwater pumping for irrigation and for city water supplies. Flow between aquifer layers is shown by double arrow heads. The aquifer rests on basement structures, which effectively represents a no-flow boundary.

The groundwater balance in table 3.1 (after Young et al. 2019) estimates groundwater withdrawals in the Indus basin at 62 billion cubic meters. This estimate is close to independent calculations by other researchers (for example, Amir and Habib 2015; Cheema et al. 2013). Combined seepage from canals and irrigation add to 44 billion cubic meters of recharge, composing more than 70 percent of inflows to the groundwater system. More importantly, this volume has already been counted as part of the surface water system and, if counted again, represents a large double counting error in the total water budget. The large component from canal seepage explains why the greatest volumes of fresh groundwater are found adjacent to these structures. The annual figure of 1 billion cubic meter depletion for the whole of the Indus basin is mainly concentrated in parts of Punjab (and mainly in the downstream portions of Bari Doab and Rechna Doab, as shown in map 3.8).

By comparison, the annual surface water balance for the Indus basin is estimated at 205 billion cubic meters (see table 3.2). Of this total, 170 billion cubic meters of this comes from Indus, Jhelum, and Chenab (Young et al. 2019).

The most significant surface water outflows from the Indus basin are canal withdrawals, which account for a net of 103 billion cubic meters per year. Other outflows are evapotranspiration losses (68 billion

FIGURE 3.13. Conceptual Model of the Indus Basin (West to East)



Note: Three layers reflect tube well pumping depths: shallow (0–35 meters deep), deep (35–90 meters), and very deep (more than 90 meters). ET = evapotranspiration.

TABLE 3.1. **Groundwater Balance for the Indus Basin in Pakistan**

Inflows	BCM	Outflows	BCM
Rainfall recharge	13	Groundwater withdrawal	62
Canal recharge	27		
Irrigation recharge (*includes recharge to areas underlain by saline groundwater*)	17		
River and flood recharge	4		
Groundwater depletion	1		
Total inflows	**62**	**Total outflows**	**62**

Source: Young et al. 2019.
Note: BCM = billion cubic meters.

TABLE 3.2. **Surface Water Balance for the Indus Basin in Pakistan**

Inflows	BCM	Outflows	BCM
Indus (including Kabul), Jhelum, Chenab	170	Gauged canal withdrawals (125 BCM) less return flow (22 BCM) (1977–2016)	103
Beas, Ravi, Sutlej	3	River and flood recharge to groundwater	4
Internal inflows	32	Natural losses (evapotranspiration)	68
		Outflow downstream of Kotri	30
Total inflows	**205**	**Total outflows**	**205**

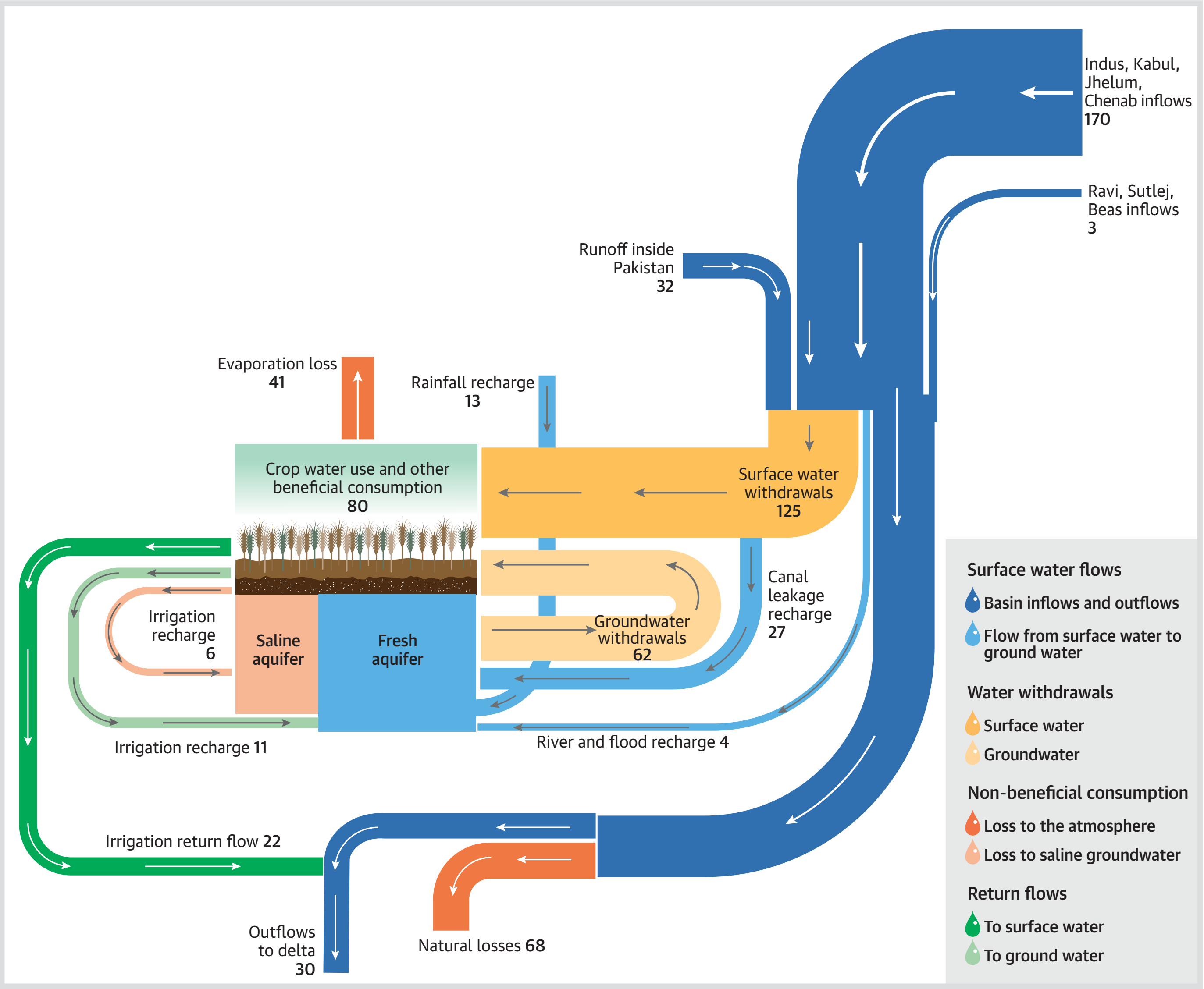
Source: Young et al. 2019.
Note: BCM = billion cubic meters.

cubic meters per year) and outflows downstream of the Kotri Barrage that average 30 billion cubic meters per year (gauged average from 1975-2016). The combined water balance, showing all inflows and outflows, is shown diagrammatically in figure 3.14. The double accounting error in the water balance becomes more evident when viewed in this way.

The groundwater balance provided in table 3.1 suggests that net groundwater depletion averages 1 billion cubic meter per year. The Indus basin aquifer is highly transmissive, and the monsoon rains and other inflows are balancing most of the pumping. Groundwater depletion is confined to localized areas in the southern reaches of the doabs, particularly the lower reaches of Bari Doab and Rechna Doab, which have deeper groundwater levels and show falling water level trends. In Sindh, freshwater zones along the left bank of Rohri Canal are also being exploited where the risk of depletion brings an added risk of upconing of saline groundwater and lateral intrusion of saline groundwater.

Table 3.3 shows the total storage of the alluvium estimated at 10,068 billion cubic meters from the saturated thickness (using June 2014 water levels shown in map 3.8) and the base of the alluvium (figure 3.1). This can be further refined to estimate the usable groundwater storage in the aquifer by taking the June 2014 EC map in panel b of map 3.8 to estimate the areas of fresh groundwater (EC greater than 1,500

FIGURE 3.14. **Indus Basin Average Annual Water Balance**



Source: Young et al. 2019.

TABLE 3.3. **Groundwater Storage for the Indus Basin in Pakistan**

Basin storage	BCM
Total groundwater storage (saturated zone)	10,068
Fresh groundwater storage[a] (EC <1,500 µS/cm)	1,256
Marginal groundwater storage[a] (EC 1,500–3,000 µS/cm)	812

Note: BCM = billion cubic meters; µS/cm = microsiemens per centimeter.

a: The thickness of the exploitable freshwater lens in Punjab was estimated at 60 meters and in Sindh at 30 meters.

microsiemens per centimeter) and marginal groundwater (EC 1,500 to 3,000 microsiemens per centimeter). The thickness of the exploitable freshwater lens in Punjab is estimated at 60 meters and in Sindh at 30 meters. The estimate of fresh and marginal groundwater storage in the aquifer is estimated at 1,256 and 812 billion cubic meters, respectively, for June 2014 (table 3.3).

Hence the usable groundwater (EC of less than 3,000 microsiemens per centimeter) in storage is 2,068 billion cubic meters, which is conservative against the estimate of 2,736 billion cubic meters by PCRWR (Khan et al. 2016). By comparison, the combined live surface water storage capacity of the three dams on the Indus was estimated in 2007 to be 15 billion cubic meters and is likely to be less by now because of ongoing sedimentation (Young et al. 2019).

Although fresh groundwater can be found at depths greater than 60 meters in the Punjab, the cost of pumping from such depths becomes prohibitively expensive for farmers. In the limited freshwater zones in Sindh, pumping is occurring from depths of 30 to 60 meters. The thickness of the freshwater lens for Sindh is assumed to be 30 meters as, below that, the risk of saline upconing is generally high.

According to some estimates, salinity affects 7 million hectares, which is 43 percent of the 16 million hectares irrigated in Pakistan's Indus basin (Government of Pakistan 2017). In 2010, the water table was reported within 1.5 meters from the ground surface over 5.25 million hectares and 3 meters from the ground surface over 9.37 million hectares. Increasing irrigation in these areas is likely to result in salinization and/or waterlogging. Managing increasing demand for groundwater will require balancing extraction and recharge to minimize the risks of waterlogging and salinity. In some areas, groundwater development appears to have reached the point where pumping is increasing in areas with marginal-quality groundwater.

Based on the water balance shown in table 3.1, the two main sources of influx of salts into the shallow aquifer are from surface water and groundwater irrigation. Taking an average salinity of surface water at 150 microsiemens per centimeter (approximately 100 milligrams per liter) and estimated average salinity in the irrigation groundwater at 1,200 microsiemens per centimeter (approximately 770 milligrams per liter), the total influx of salt to the groundwater of the Indus basin is about 16 million tons per annum. Some salt also flows back into rivers or is trapped in localized sinks, and some outflows from the Left Bank Outfall Drain (LBOD). These need to be accounted for but would be small in comparison to the salt that is added by groundwater irrigation. A much larger volume of salt is estimated to accumulate annually in the soil (Yu et al. 2013) and also in the unsaturated zone (the part of the aquifer that sits above the water table) because of evaporation.

Groundwater Stresses

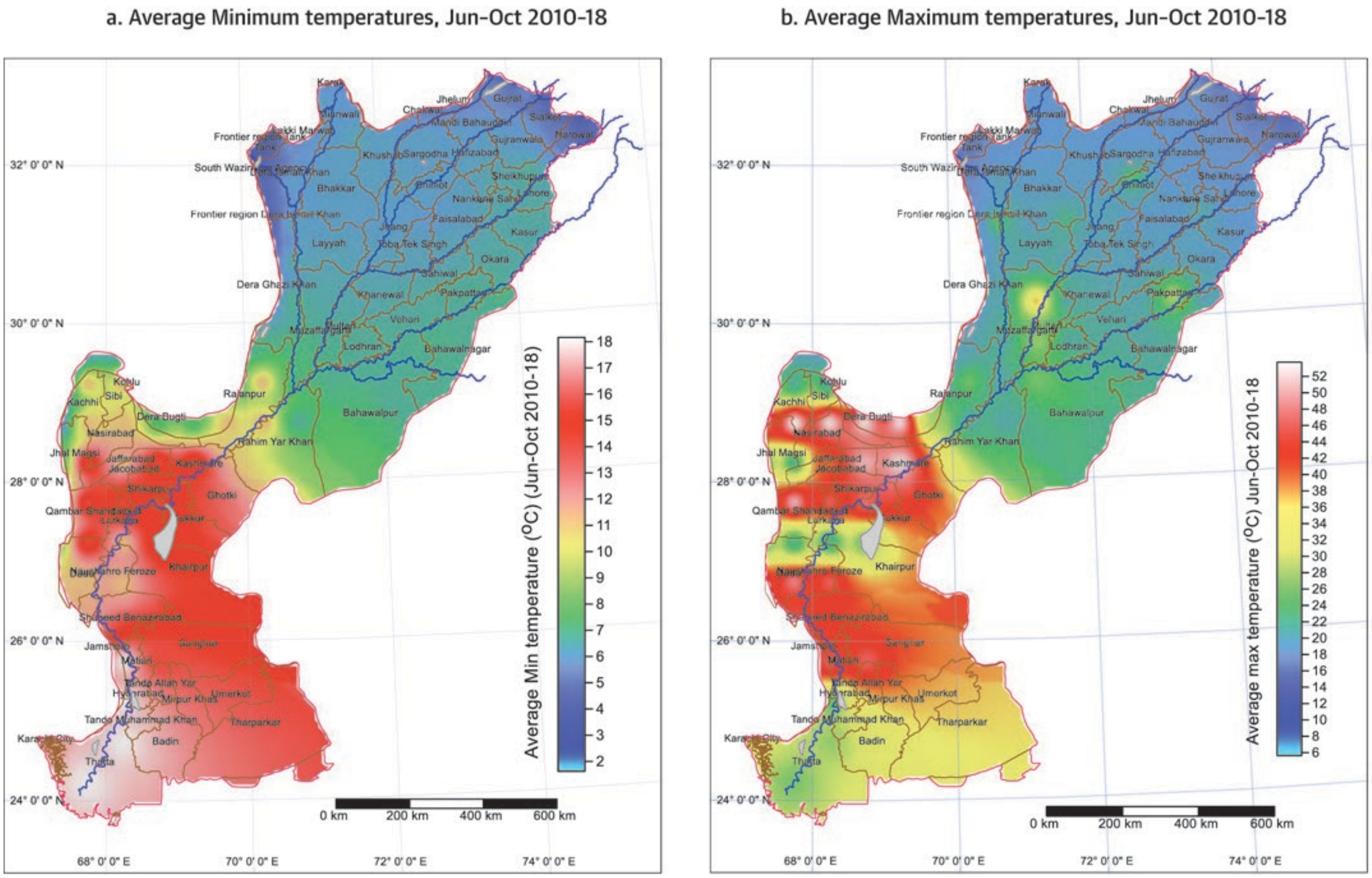
The ratio of groundwater withdrawal relative to the recharge rate for a groundwater system is one measure of the stress on the aquifer. When pumping stresses or unsustainable groundwater extractions exceed recharge over the longer term, it affects the availability of groundwater and dependent ecosystems, such as rivers and lakes. Changes to evapotranspiration and rainfall are important, but by far the major stress on Indus basin groundwater is the level of abstraction in Punjab from more than a million tube wells and the increasing number of tube wells in the freshwater zones in Sindh.

Rainfall and Evapotranspiration

There are significant temperature and precipitation variations across the Indus basin. As a general trend, it is observed that average temperatures increase from north to south, whereas rainfall decreases. Lack of rainfall is particularly acute for regions of southern Punjab and Sindh. This means that water requirements for crops in both Kharif and Rabi seasons increase as one moves from upstream reaches of the Indus basin to downstream areas. However, the variation of both parameters within Punjab and Sindh are shown prior to discussing the relationship between climate and groundwater stress.

Average minimum temperature[7] (2010-18) for Kharif season from June to October varies from below 2°C in the northern regions of the alluvial plains to 18°C and during Rabi season from below 2°C to 14°C. Minimum temperatures are highest in Sindh, particularly in the delta regions. Average maximum temperatures vary from 6°C to over 52°C during Kharif with the hottest temperatures in Jacobabad, Nasirabad, Kashmore, followed by Shikarpur, Benazirabad, and Jamshoro. During Kharif, the monsoon brings relief from high temperatures in the Indus delta and coastal districts of Sindh (map 3.9). The maximum temperatures during Rabi season range from 6°C to over 40°C, and the hottest areas in Sindh are similar to the hottest

MAP 3.9. Average Temperatures in Pakistan



a. Average Minimum temperatures, Jun-Oct 2010-18

b. Average Maximum temperatures, Jun-Oct 2010-18

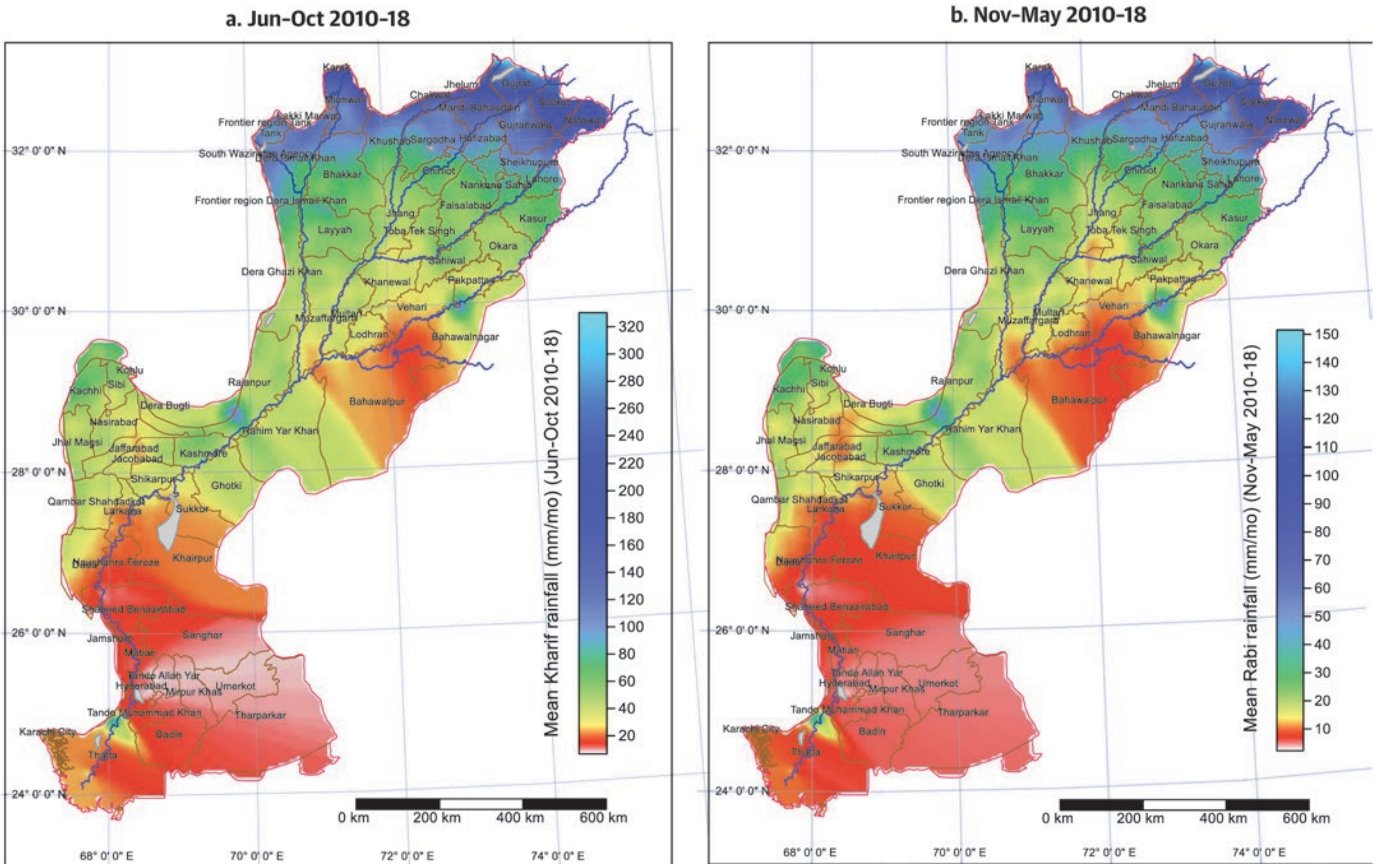
Source: Original compilation, using data from the National Oceanic and Atmospheric Administration (NOAA).

areas during Kharif. There are some exceptions—the average maximum temperatures in the delta and coastal areas of Sindh are warmer during Kharif. There are also localized areas with relatively high temperatures in southern Punjab in districts Muzaffargarh, Lodhran, and Bahawalpur during Rabi.

Bonsor et al. (2017) state that about 10 to 20 percent of rainfall recharges the alluvial aquifer in the less arid parts of the Indus basin in Pakistan. This is an important contribution to groundwater volume as well as to reducing root zone salinity. The variation in mean monthly rainfall across the basin—shown in map 3.10—for Kharif ranges from less than 20 millimeters in the southern regions of the basin to more than 320 millimeters in the northern regions. During Rabi season, the rainfall varies from less than 10 millimeters to more than 150 millimeters, considerably less than in Kharif. Rainfall in Sindh tends to be lowest in the districts of Umerkot, Mirpur Khas, Tando Allahyar, and Hyderabad. The highest rainfall during both Kharif and Rabi seasons is in the northern regions of the doabs in the districts of Narowal, Sialkot, Gujrat, Jhelum, and Mianwali.

The mean monthly potential evapotranspiration[8] (ET) for Kharif season varies between 40 millimeters in the northern regions of the doabs in Punjab to a high of more than 180 millimeters in southern Punjab and

MAP 3.10. **Seasonal Precipitation in Pakistan**



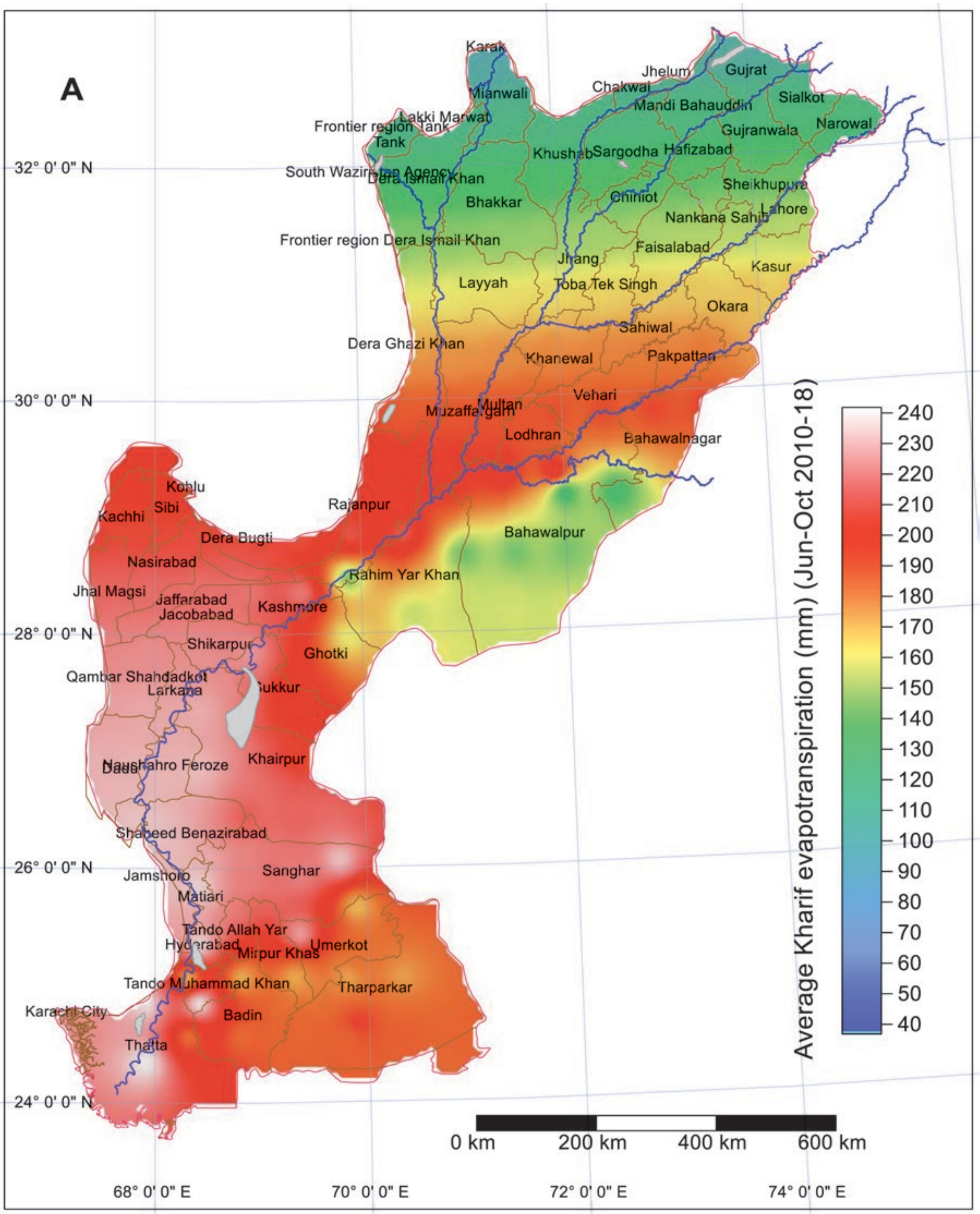
a. Jun-Oct 2010-18

b. Nov-May 2010-18

Source: Original compilation, using data from the National Oceanic and Atmospheric Administration (NOAA).
Note: Average in millimeters/month.

more than 240 millimeters in Sindh. Potential evapotranspiration and higher temperatures are the main drivers for consumptive use in an irrigated area. The spatial variation of evapotranspiration in map 3.11

MAP 3.11. Seasonal Potential Evapotranspiration, Jun–Oct 2010–18



Source: Original calculations using climate data from the Global Data Assimilation System (GDAS).
Note: Average in millimeters/month.

shows very high crop water demand in Sindh in Kharif season. Demand is significantly less in the northern reaches of the doabs—with higher rainfall and better access to surface water and groundwater, crops are less likely to be stressed in these regions. In southern Punjab and Sindh, extremely hot conditions during Kharif, coupled with high evaporative demand, means that effective water management is essential for improved crop production and to ensure that crops are not heat and water stressed. The timely delivery of surface water becomes even more critical in those areas that do not have access to good-quality groundwater for supplementary irrigation and in which evaporative demand and the risk of heat stress on crops are high.

Decreasing rainfall and increasing crop water requirement toward the tail end of canals results in increased groundwater depletion. Climate variability will further intensify the ongoing water shortage at the tail ends because of operational and administrative constraints (difficulty in hydraulic control along the long canals and theft of water). The poor status of knowledge and control over canal deliveries, combined with the poor knowledge of the groundwater status (levels and salinity) in Pakistan, prevents making meaningful changes to irrigation duties and taking advantage of the opportunity for conjunctive management.

Climate Change

Historical trends show statistically significant increasing temperatures and annual precipitation for the past century over the whole of Pakistan (Yu et al. 2013). General findings from a range of general circulation model (GCM) outputs show continued increases in temperature estimated to be close to 3°C warmer by the 2050s. These models are more reliable for the irrigated plains than the mountainous upper basin (Yu et al. 2013). There is also some indication of a general trend in increased precipitation during the summer and a decrease during the winter (Yu et al. 2013).

The large volumes of groundwater in storage in the Indus basin present a considerable buffer against future variability in surface water flows and temperatures, and the importance of the resource is likely to rise in consequence. Recharge across the Indus basin is a nonlinear function of rainfall volume and intensity—below certain thresholds of rainfall volume, recharge to groundwater is considerably lower (Bonsor et al. 2017). Global climate models do not concur on future changes to precipitation patterns, especially the timing and intensity of the monsoon (BGS 2015).

The extent and rate of melting of glaciers and snowpack in the Himalaya have a large influence on the flow of the Indus River (Yu et al. 2013) and hence on its quality (that is, capacity to dilute salts), but predictions for this also remain uncertain under future climate change scenarios. Although it is likely that groundwater abstraction in the Indus basin will remain the primary stress on the aquifer, increases in such abstraction may be a consequence of higher temperatures and lower surface water availability and/or quality. For these reasons, the potential changes to the basin predicted by climate change models should be included in long-term basin planning and updated as new data emerge.

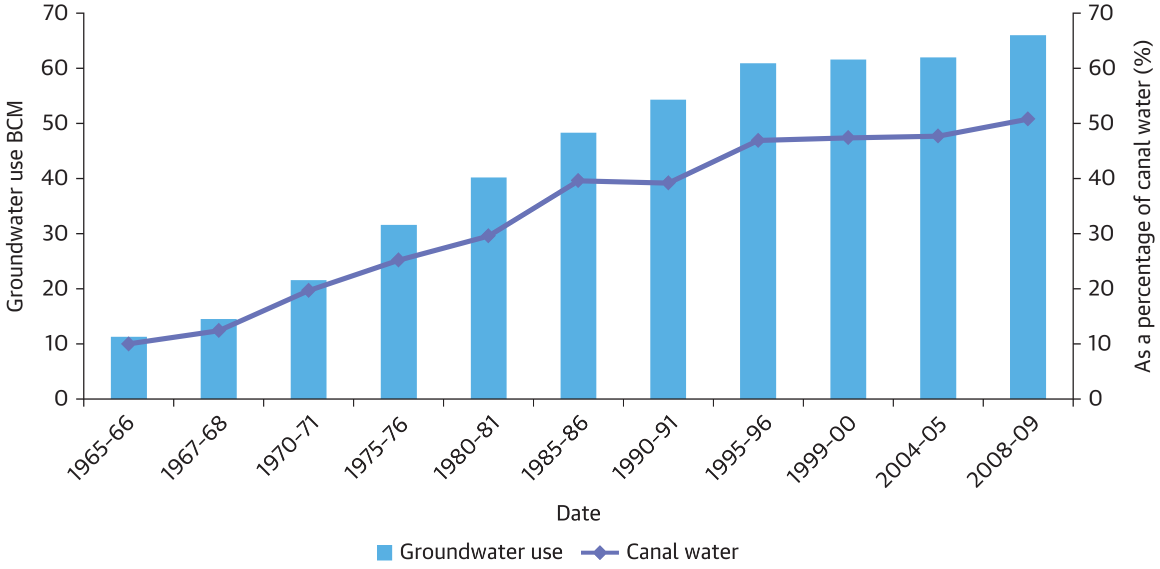
Pumping Volumes

Quantifying groundwater abstraction in Pakistan’s Indus basin is challenging as data are scarce. The few studies that have been undertaken have mostly relied on the proxy approach of estimating the number of tube wells in each district, and the discharge capacity and operational hours of tube wells, to arrive at an estimate of pumping volume. The operational hours are calculated from electricity and fuel usage or through surveys in that irrigation scheme. These estimates are not always reliable given the inadequacy of the data. Pumping is the most important stress on the Indus basin aquifer, and the absence of any metering of pumping hampers a meaningful understanding of it as Pakistan grapples with managing water shortages for agriculture, industry, and domestic use.

The total groundwater pumping estimated by Young et al. (2019) for the Indus basin is 62 billion cubic meters (see table 3.1), though estimates range from 62 billion to 70 billion cubic meters and indicate that the pumping stresses on the Indus basin aquifer are significant. Of the estimated total 62 billion cubic meters of groundwater abstracted from the Indus basin, about 90 percent (55.8 billion cubic meters) is used in Punjab and the rest (6.2 billion cubic meters) is used in Sindh (ACE, AGC, and SMEC 2011). The increasing volume of groundwater pumping from 1965–2009 and its expression as a percentage of canal water use is shown in figure 3.15.

Groundwater extraction is common throughout Punjab, though in areas where groundwater is saline, this is restricted to the seepage zones adjacent to canals. In general, the increasing dependency on groundwater for irrigation contributes to aquifer depletion, high pumping costs, and water-quality degradation. In many districts, groundwater levels dropped by about 3 meters in the five years from 2005 to 2010 (Friends of Democratic Pakistan 2012). The increasing practice of abstracting more water than the replenishment rate of the aquifer is inducing groundwater quality problems leading to land degradation and loss of agricultural production. For example, in the Lower Bari Doab Canal command area, where groundwater contributes 53 percent of the irrigation and groundwater extraction exceeded the groundwater recharge in 2007, the groundwater quality deteriorated in several locations, leaving 50 percent of

FIGURE 3.15. Groundwater Pumped as a Percent of Canal Water



Source: Adapted from ACE, AGC, and SMEC 2011.

the groundwater usable, 32 percent of marginal quality (which is often mixed with fresher surface water to achieve a manageable salinity), and 18 percent hazardous (IWASRI 2011). In Rechna Doab, the salinity of groundwater can exceed 3,000 microsiemens per centimeter in the mid-regions of the doab (Punthakey et al. 2015), a level detrimental to crop yield. Sustainable groundwater use in Punjab in future will depend on improved groundwater management and strict enforcement of groundwater regulation, especially in hotspots.

Although more limited in Sindh, fresh groundwater is found in all six districts in the Rohri Canal command area within 20 to 60 meters from the surface. In Naushahro Feroze, Shaheed Benazirabad, and Matiari districts, farmers are extracting fresh groundwater from between 25 and 40 meters in depth, and in Hyderabad and Tando Muhammad Khan districts, groundwater extraction varies from 30 to 60 meters. In some areas of Tando Muhammad Khan and in Tando Allahyar district, groundwater is extracted from as much as 75 meters below ground level. In general, much of the groundwater in Sindh is exploited from shallow depths by exploiting the freshwater lens that has built up as a result of seepage from unlined main and branch canals. In addition, there are also permanent relatively thick freshwater zones in the riverine areas that are connected to the rivers—and anecdotal evidence that the aquifers there are being overexploited. Parts of the desert areas in the east of Sindh also rely on groundwater, though much of it is not receiving present-day recharge (Geyh and Ploethner 2008) and some areas contain very high concentrations of nitrates (Soomro et al. 2017).

In Sindh, groundwater is used in 20 percent of irrigated areas, as groundwater with marginal to high salinity levels is more widespread. However, groundwater use for irrigation is increasing in Sindh with fresh groundwater development schemes initiated by the public sector, which exploited the available freshwater lens along main canals, such as Rohri Canal. With the services provided by drillers, private tube well installation by farmers in Sindh has increased where there are readily available freshwater lenses. Field observations[9] indicate there has been a substantial increase in groundwater exploitation along the left bank of the Sukkur Barrage between the Indus River and the Rohri Canal and in the Rohri Canal command, which covers the districts of Sukkur, Khairpur, Naushahro Feroze, and Shaheed Benazirabad. These areas of relatively higher groundwater exploitation require particularly regular monitoring.

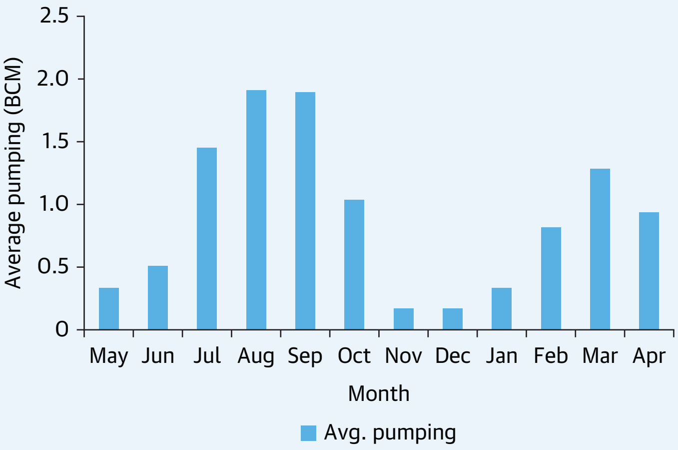
Although groundwater extraction in Sindh is much lower than that in Punjab, it nevertheless imposes stress on the aquifer as the groundwater is extracted from thin freshwater bodies that have accumulated over time as a result of seepage from the canals and irrigation return flows, as well as from the thicker, permanent aquifer systems naturally connected to the Indus River. The stress on the aquifer system is in the form of declining groundwater levels and resulting deteriorating water quality in the limited freshwater zones.

There are no records of groundwater pumping volumes in any of the doabs in Punjab or any location in Sindh as groundwater usage is not monitored. In the absence of directly measured data, specific studies on groundwater have applied innovative methodologies for deducing or estimating pumping rates. Box 3.2 illustrates a method for facilitating groundwater decision making in the absence of pumping data, and of the possible applications of pumping data.

BOX 3.2. Estimating Pumping in the Rechna Doab

Punthakey et al. (2015) used remote sensing for mapping crops and estimating actual evapotranspiration on a monthly basis from 2008 to 2014 in Rechna Doab and estimated recharge from rainfall and irrigation recharge. Pumping was then estimated as the difference between the spatial estimate of recharge and actual evapotranspiration. This approach provides an estimate of the pumping spatially and temporally, but it does introduce potential errors. For instance, it was assumed that farmers irrigate their crops to meet the consumptive requirement of the crop, but in reality many farmers overirrigate depending on the availability of water, and so pumping may be underestimated. Conversely, pumping may be overestimated in areas where surface water provides a significant proportion of irrigation water, or where farmers may be pumping only small amounts of groundwater because of water quality constraints. The estimated pumping from Rechna Doab for Kharif and Rabi seasons in figure B3.2.1 shows average monthly groundwater usage varies from 0.17 billion cubic meters in November and December during Rabi season to a high of 1.91 billion cubic meters in August during Kharif season (Punthakey et al. 2015). The average pumping for the entire Kharif (June to October) is 6.8 billion cubic meters and 4.03 billion cubic meters for Rabi (November to May).

FIGURE B3.2.1. Average Estimated Pumping in Kharif and Rabi Seasons, 2008–13



Source: Punthakey et al. 2015.

Metering of tube wells at strategic locations within the basin to provide spatial coverage of pumping and identifying screen depths to understand the depth from which groundwater is being pumped would reduce uncertainties and provide improved information on the state of the aquifer for regulators. Sustainable extraction limits for groundwater management areas will require water quantity and quality considerations to ensure access to good-quality groundwater for future users. The Rechna Doab study improved understanding of the sustainability of groundwater usage

box continues next page

BOX 3.2. continued

there, useful for modeling scenarios for the management of surface water and groundwater in the doab. The main finding recommended an estimated sustainable yield from Rechna Doab of 10±1 billion cubic meters and recommended an upper limit of 1 billion cubic meters to allow for adaptive management during drought periods when pumping is expected to increase as the demand for irrigation increases (Punthakey et al. 2016). An adaptive management approach would allow for moderating pumping during years when surface water supplies are plentiful, allowing replenishment of the aquifer and minimizing salinity increase as a result of groundwater pumping. The trend in Rechna Doab has been an increase in groundwater pumping with more than 200,000 tube wells using groundwater. This brings into question the resilience of the system, given that the Punjab Irrigation Department does not have the institutional structure nor the regulatory mechanisms in place to enforce the recommended sustainable yield.

Salinity, Irrigation, and Waterlogging in the Indus Basin

Salinity in the Indus basin is primarily natural, and terrestrial in origin (except in the delta region), and can become concentrated in groundwater by natural and anthropogenic activities (MacDonald et al. 2016; Naseem and McArthur 2018), as shown in figure 3.15. As the aquifers of the Indus plain are generally unconfined and connected to the rivers and irrigation system, water quality in agricultural areas is influenced by seepage from the canal network, recharge from irrigation, and return flows from groundwater irrigation. Waterlogging occurs where the groundwater level is within 1.5 meters of the ground surface and cannot drain away, particularly where barrage-controlled irrigation networks combined with excessive irrigation have raised the water table. Evaporation from the high water tables concentrates salts in the shallow subsurface from irrigation water that already contains high salt levels and may also contain nitrates. These twin problems lead to degraded soil, loss of production and increased public health risks.

The problem in Pakistan has been observed for many decades—the situation in Punjab even attracted the attention of the U.S. government in the early 1960s (The White House 1964) as it was considered to pose a security threat. The ongoing impacts of waterlogging and salinity on water quality and agricultural productivity are higher in Sindh as compared to Punjab. A major reason for this is the low levels of pumping and poor drainage infrastructure in areas where barrage-controlled irrigated agriculture has raised the water tables. Even though pumping has increased in Sindh, especially in riverine and canal command areas, it still amounts to less than 20 percent of the surface water volume used for irrigation. By comparison, the use of surface water and groundwater in Punjab is almost equal.

Pre- and post-monsoon water-level data for the Indus basin in 2014, as shown on map 3.8, indicate that waterlogging affects substantial areas even in "normal" years. However, in 2011 severe flooding in mid- and Lower Sindh resulted in waterlogging, affecting an additional 2.19 million hectares following the 2011 monsoon (Lashari et al. 2015). In Sindh, 70 percent of the irrigated area was waterlogged with water tables within 1.5 meters, and 36.0 percent of the land was severely waterlogged with the water table within 1 meter.

Waterlogging and salinity in Sindh appear to be persistent in canal command areas served by nonperennial canals. These canals receive excessive supplies in Kharif season, which raises the water table and brings salts to the surface, whereas the lack of surface water during Rabi season available for flushing facilitates salt accumulation at the soil surface. This has implications for surface water allocations for irrigation and the management of the two resources in a conjunctive manner (see chapter 5).

Sindh has more widespread surface salinity as a result of capillary rise from areas with high water tables. Freshwater zones at depths of less than 15 meters below ground level cover about 46 percent of irrigated areas in Sindh. These areas are tapped by shallow bores and hand pumps, which provide domestic water.

Water can be broadly classed according to the following salinity ranges:

<1,500 mg/l	usable
1,500–3,000 mg/l	marginal
>3,000 mg/l	brackish

Note: mg/l = milligrams per liter.

Estimates suggest 60 to 75 percent of the groundwater in the alluvial aquifer of the Indus basin is marginal to brackish in quality (Young et al. 2019). Groundwater salinity varies widely, ranging from less than 1,000 to greater than 3,000 milligrams per liter and, in the southern regions of Sindh, can exceed 3,000 milligrams per liter. The lack of canal water supply to tail-end farmers is resulting in increased reliance on marginal-quality groundwater, as the underlying groundwater in the mid-doab regions is of marginal quality. Using this groundwater increases salinity in the root zone and increases sodicity when groundwater has sodium adsorption ratio (SAR)[10] of greater than 6. Irrigation of crops with groundwater of high salinity and sodicity leads to a deterioration of soil structure and accumulation of salts in the root zone, which in turn decreases crop productivity. As a result, Punjab now suffers increasing pumping costs and salinity because of declining groundwater levels in areas that previously had high water tables (see box 3.3).

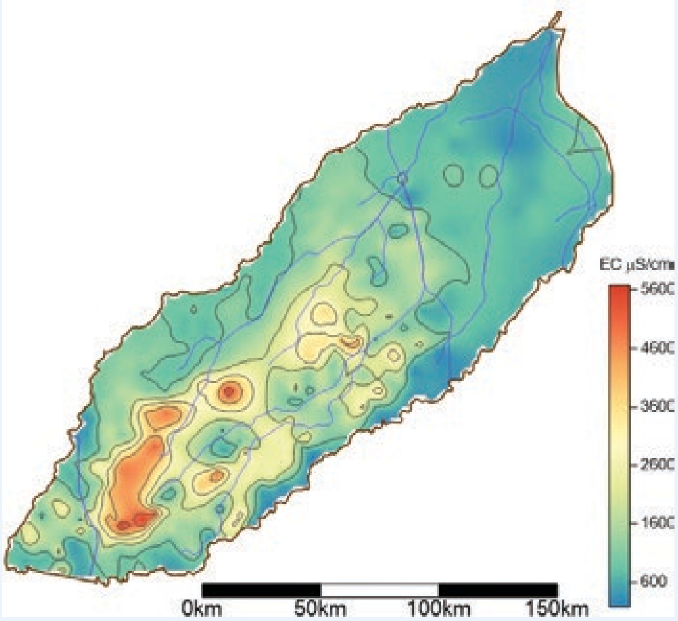
In Sindh, shortages of good-quality canal water have pushed farmers to supplement it with poor-quality groundwater, which is increasing the concentration of salts across irrigated areas. A study on water quality in Sindh by Mahessar et al. (2017) found EC ranged from 2,000 to 9,000 microsiemens per centimeter and TDS ranged from 1,000 to 6,000 milligrams per liter.

A review paper by Foster et al. (2018**)** cautioned on the need to evaluate salt balances periodically at aquifer subregional levels to assess the risk of salinization of groundwater recharge. Irrigation with groundwater, which has higher dissolved salts than canal water, leads to salts leached from permeable soils to groundwater by irrigation return flow. Foster et al. (2018) correctly observed that seepage from canals can provide helpful dilution because usually canal water is low in salinity. However, the continual use of groundwater for irrigation will increase the risk of secondary salinization, so avoiding degradation relies on maintaining an awareness of salt balances and trends.

BOX 3.3. Rechna Doab: Need for Managing Water and Salinity

Extreme drought conditions from 1996 to 2001 reduced the surface water availability in Punjab by 46 percent. Farmer demand for water was displaced to groundwater, and the number of private tube wells increased by 59 percent (Qureshi, Shah and Akhtar 2003). In the upper reaches of the doabs and at the heads of the canals that are underlain by fresh groundwater, farmers supplemented surface water supplies with groundwater to meet crop water requirements and to increase cropping intensities. Farmers in the mid-portions of the doab and at the tail ends of canals had to cope with scarcity of irrigation water. These areas are typically underlain by saline groundwater, and its use for irrigation led to decreased crop productivity and increased salinization and sodicity. An example of salinity concentrations for Rechna Doab is shown in figure B3.3.1 (Punthakey et al. 2015). Monitoring and management of groundwater pumping is just as important in these zones as in the freshwater zones.

FIGURE B3.3.1. **Salinity EC, October 2012, for 30- to 60-M-Deep Layer for Rechna Doab**



Source: Punthakey et al. 2015.
Note: EC = electrical conductivity; μs/cm = microsiemens per centimeter.

The absence of groundwater management and enforcement of a groundwater regulatory framework means these issues are unresolved in Rechna Doab. Increasing use of groundwater and increased pumping where groundwater salinity levels are high are cumulating risks for irrigated cropping systems in the mid-portions of Rechna Doab.

Nonbeneficial evaporative losses occur in both fresh and saline groundwater zones, with 25 percent of these losses coming from freshwater areas and 75 percent from saline areas. Saline groundwater tables, which are very high and within the root zone, have a serious impact on drinking water in the lower left bank areas of Badin and Thatta. In the coastal region of the Indus basin, marine influence is a major factor contributing to elevated salinity levels in groundwater (see box 3.4), and in Thatta district, there is evidence of seawater intrusion into shallow unconfined aquifers (Naseem, Husain, and Bano 2018). The Lower Indus Project study (Hunting Technical Services 1965) showed that salinity levels are very high below Kotri Barrage with values increasing with depth. The depth range from 61 to 91 meters exceeds salinity of seawater (35,000 parts per million). Details of studies undertaken in the region of the Indus basin below Kotri Barrage are presented in appendix A. Farther from the coast, a combination of factors—including low gradients, lack of drainage, and high water tables caused by irrigation—brings low-quality groundwater within the crop root zone.

Demographic Changes

The anticipated changes in population (see chapter 2) and the associated pressures on water availability for specific sectors over the coming three decades are likely to place a significant stress on groundwater, possibly equal to any of the other factors mentioned here. The poor understanding of groundwater resources, lack of protection, and underprovisioning for many essential uses that rely on this resource foreshadow the challenges of the future as the population becomes more urbanized and water resources become locally scarce.

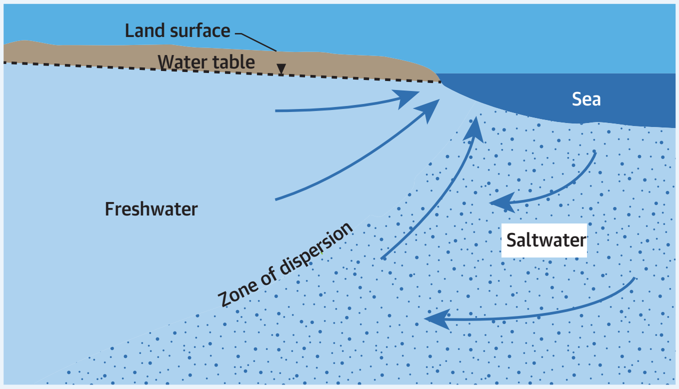
BOX 3.4. Seawater Intrusion

The freshwater and saltwater zones within coastal aquifers are separated by a transition zone within which there is mixing between freshwater and saltwater. Within the transition zone, freshwater flowing to the ocean mixes with saltwater by the processes of dispersion and molecular diffusion. This difference in density results in seawater lying beneath the freshwater on the landward side of the coastline, known as the Ghijben-Herzberg Principle (Post et al. 2018). In practice, the fresh and saline waters are miscible, which results in a mixing zone, the thickness of which depends on hydrodynamics of the aquifer. The shape of the interface will generally be similar to that shown in figure B3.4.1, with a steep slope in the shallowest part of the aquifer grading to a gentler slope at depth. This change of slope may create a "toe" of saltwater extending into the aquifer beneath the freshwater. The interface is likely to be diffuse, depending on prevailing conditions. The position, shape, and sharpness of the interface depend on the degree of balance between the head conditions in the aquifer and the sea level and the flow conditions that prevail. The extent of the toe into the aquifer beneath the freshwater will depend in part on the depth to the base of the aquifer. In a very shallow aquifer, there may be essentially no toe, and the steep part of the interface will extend to the base of the aquifer.

box continues next page

BOX 3.4. continued

FIGURE B3.4.1. Interface between fresh and saline groundwater in coastal areas



Source: After USGS n.d.

A number of factors can affect the position of the interface:

- Seasonal changes in natural groundwater flow
- Tidal effects
- Barometric pressure
- Dispersion
- Climate change and sea level rise

What Causes Seawater Intrusion

Seawater intrusion is caused primarily by the reduction of head in the aquifer along the coast and the subsequent reduction of freshwater discharge to the sea as a result of groundwater abstraction and/or reduction in river discharge. Reduction in freshwater discharge to the coastal boundary will result in the saltwater wedge moving inland as flushing with freshwater decreases. The thickness of the wedge increases, leading to a new equilibrium.

Groundwater abstraction above a freshwater-saltwater interface causes upconing. Depending on aquifer characteristics, well penetration, and pumping rate, a stable situation may be attained where saltwater does not reach the well. However, when this critical state is exceeded, saltwater enters the well and mixes with the fresh water, which decreases the quality of the discharge.

Climate change resulting in a rise in global mean sea levels is likely to threaten vulnerable coastal aquifers. The impacts will be felt first in low-lying coastal areas and deltaic zones where land elevations are within a few meters above or below sea level and include increased saltwater intrusion into coastal aquifers and a further shift inland of the mixing zone between fresh water and seawater. This could also threaten many groundwater wells in coastal regions because of a higher risk of upconing of saline groundwater and a resulting decrease in water quality from these wells.

Groundwater Quality in the Indus Basin

Groundwater quality in Pakistan is as serious an issue as groundwater levels. Salinity, though also a water quality issue, is discussed earlier with waterlogging because of its close link to the extraction and use of groundwater for irrigation. Map 3.12 shows groundwater in the irrigated part of the Indus basin, classified according to its salinity class (fresh, marginal, and hazardous).

In Pakistan, more than 70 percent of drinking water comes from groundwater that is recharged from the Indus basin irrigation system (Chandio, Abdullah, and Tahir 1999; Imran et al. 2016), and as much as 80 percent of the population is exposed to unsafe drinking water (Daud et al. 2017). Tracking the trajectory of water quality deterioration is possible only in a general sense as data on the temporal and spatial extent of the problem are not collected routinely. Poorly constructed wells are a known source of contamination of extracted groundwater in many countries (Custodio 2013), and hand pump headworks and wells have been shown to harbor sources of microbial contamination even when the groundwater in the aquifer is not contaminated (Osborne et al. 2018).

Many of the studies on water quality in the Indus basin are localized studies that focus particularly on urban areas. Water quality monitoring often excludes rural and remote areas, where drinking water contamination may be severe (Khan, Haq, and Saeed 2012). Such reports as are available tend to present the information as interpreted maps, and locations of collected samples are vague or part of PhD theses that are not publicly available. Regional-scale risk assessments are often not available, and estimates of the population at risk are difficult. As with groundwater levels, the limited data on groundwater quality complicate its assessment and add uncertainty to policy. Furthermore, much is often unknown regarding the nature of groundwater contamination (for example, natural salinity, microbiological contamination, industrial pollution). Well-known sources of contamination for surface water, such as sugar mill effluent and tanneries, may be assumed to contribute to groundwater contamination, even if not measured.

Although not discussed further here because of lack of data, groundwater contamination by pesticides is reported (Azizullah et al. 2011), and contamination by organic compounds (for example, polycyclic aromatic hydrocarbons [PAHs], pesticides, dense nonaqueous phase liquids such as chlorinated solvents, and other industrial pollutants) is suspected in urban and industrial areas (Raza et al. 2017).

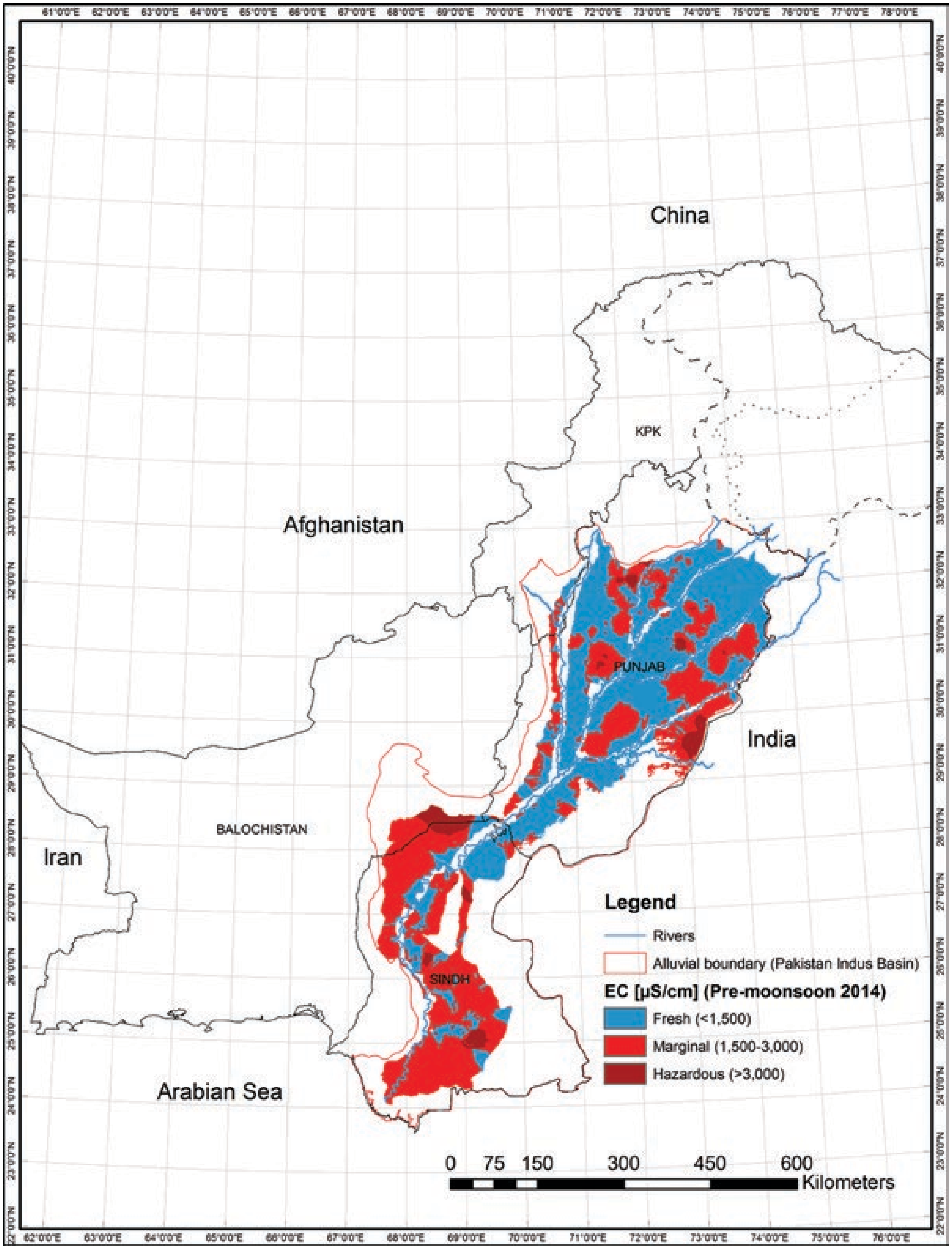
The following subsections describe the different categories of contaminants affecting groundwater quality in the Indus basin.

Chloride, Nitrate, and pH

Apart from waterlogging and salinity, other important chemical parameters and indicators of groundwater quality include chemically conservative species, such as chloride and nitrate, as well as pH. Chloride and nitrate may be added by agricultural fertilizers, and both are also related to contamination of groundwater by poorly treated wastewater.

A groundwater quality study by PCRWR (Malik, Azam and Saboor 2010) of mountainous areas falling outside the alluvial Indus basin, and including Mardan, Swat (both upper and lower), Buner, Gilgit, Ghanche, Diamere and Ghizer showed that the chemical groundwater quality of the five northern

MAP 3.12. **Location of Fresh and Saline Groundwater in the Indus Basin of Pakistan**



Source: Original compilation.

mountainous districts in Khyber Pakhtunkhwa was generally good. However, this study also revealed nitrate contamination in all five districts, attributed to runoff and erosion on steep slopes and transport of fertilizer downstream, as well as biological contamination of unprotected water sources. This finding is an important illustration of the need to understand and account for the downstream impacts of activities.

The results of a wide-ranging sampling program (Podgorski et al. 2017) are shown in map 3.13 for chloride (Cl), EC, nitrate (NO_3), and pH. Higher values of Cl and EC are clustered along the irrigated areas and in southern Sindh, which is consistent with other studies in Sindh and probably indicates natural salt concentrations and evaporative concentration. The northern parts of the country generally have lower EC values and increase toward the south (as shown in map 3.8), with the highest EC sampled exceeding 10,000 microsiemens per centimeter. Higher values of NO_3 are clustered toward the north and northwest of the country and in the south and probably indicate anthropogenic pollution of shallow groundwater. The range in pH values is from 6.14 to 8.75, with no obvious spatial pattern discernible.

Analysis of groundwater in Bahawalpur Tehsil in southern Punjab was undertaken to test its suitability for irrigation (Riaz et al. 2018). Results showed that 52.8 percent of samples were unfit for irrigation because of high values of EC, SAR, or residual sodium carbonate index (RSC).[11] The sampled range of EC was 31 to 15,390 microsiemens per centimeter, SAR ranged from 0.02 to 52.66 (greater than 6 means unfit), and RSC ranged from 0.031 to 15.39 me/l (milliequivalents per liter) (greater than 2.5 me/l means unfit). The study showed that water samples from tube wells over a large area had high values of all three.

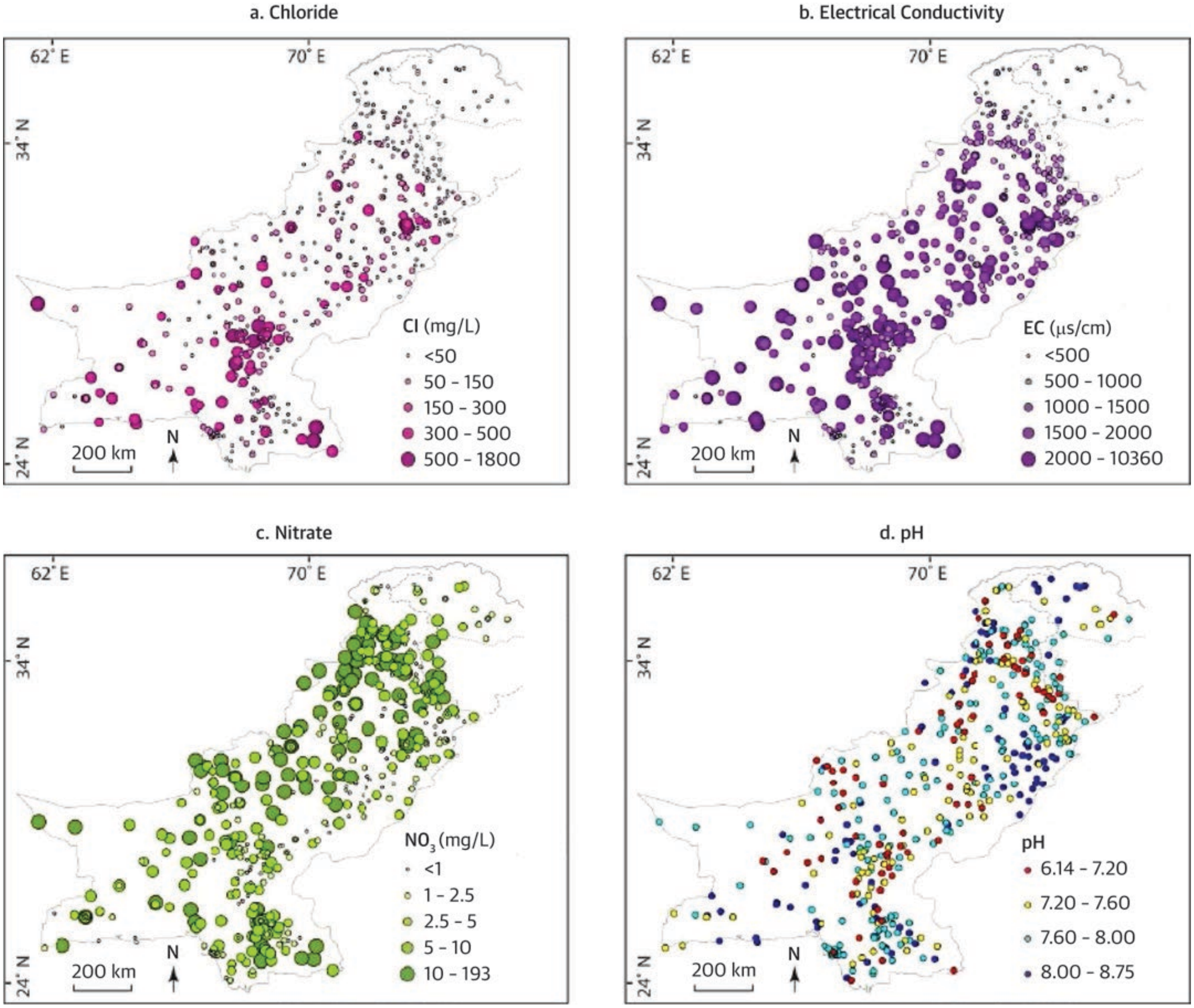
Within the lower Indus basin, the shallow aquifer in the irrigated and coastal regions were studied by Shahab et al. (2019) to determine their vulnerability to groundwater contamination from surface pollutants: 56.8 percent of the area was deemed highly vulnerable, 28 percent was very highly vulnerable and was located mostly in the upper northern and southernmost coastal area of Sindh, and 15.2 percent was considered a medium vulnerable zone. Sensitivity analysis of DRASTIC[12] parameters indicated depth to water table and net recharge caused the highest variation in the vulnerability index.

Microbiological Pollution of Groundwater

Microbiological pollution of groundwater in the Indus basin poses one of the greatest immediate health risks for populations dependent on groundwater for domestic purposes (Mansuri et al. 2018). Studies in Sindh found that contamination levels are amplified by its heavier dependence on hand pumps, which typically extract water from shallower aquifers, compared with motorized pumps, and water sources for domestic use frequently exceeded national and WHO standards for coliform bacteria (Alamgir et al. 2016; Memon et al. 2011). Poorly designed soak pit toilets (and non-engineered septic tanks) and shallow groundwater wells increase groundwater contamination (Mansuri et al. 2018).

Waterlogging may also support an environment in which microbial contamination thrives. A comparison of fecal-oral diseases (diarrhea and dysentery) taken from a study of the effects of irrigation projects on the health of rural population in Sindh (Punthakey et al. 1997) shows a major peak in infantile

MAP 3.13. **Maps of Spatial Distribution and Values of Selected Chemical Parameters**


a. Chloride

b. Electrical Conductivity

c. Nitrate

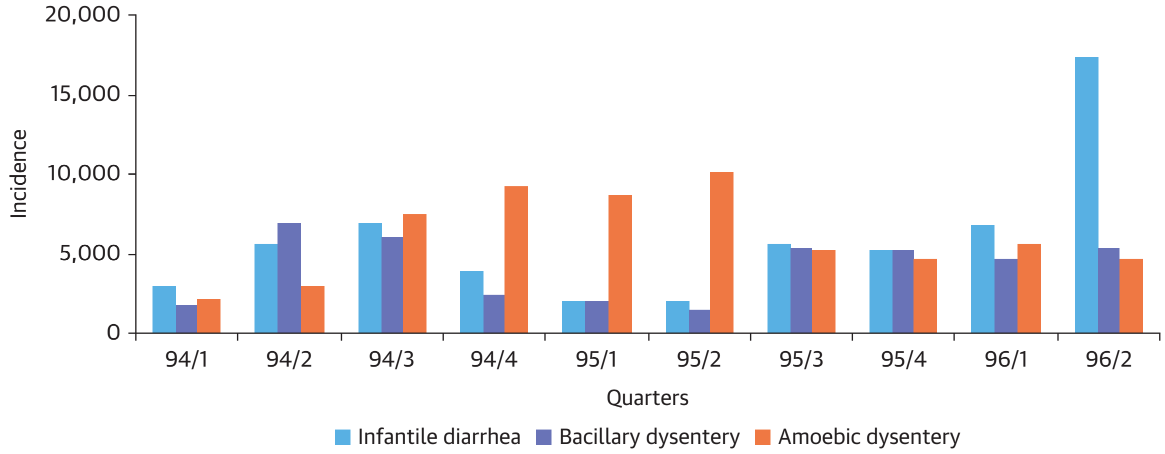
d. pH

Source: After Podgorski et al. 2017.

Note: Cl = chloride; EC = electrical conductivity; NO$_3$ = nitrate.

diarrhea in the second quarter of 1996 and peaks in amoebic dysentery from the fourth quarter in 1994 to the second quarter in 1995, shown in figure 3.16. This may be related to the very wet monsoons in 1994 and 1995, which left vast areas inundated for several months after the wet season. The incidence of hepatitis shows a similar pattern to amoebic dysentery with peaks occurring between the fourth quarter of 1994 to the third quarter of 1995. A similar epidemic of malaria during the fourth quarter of 1995 and an epidemic of typhoid in the first quarter of 1995 were also recorded.

FIGURE 3.16. Incidence of Water-Borne Diseases in Lower Sindh



Source: After Punthakey et al. 1997.

Groundwater also gets contaminated by agricultural and municipal wastewater. Microbial contamination of drinking water supplies in urban areas is of particular concern because of the concentration of potential contamination sources, such as sewerage pipes and polluted surface water bodies.

Lack of solid waste management, discharge of untreated wastewater, and leakage from sewerage contaminate surface water and groundwater supplies in all major cities of Pakistan. A countrywide groundwater quality study in urban areas by PCRWR (Kahlown, Tahir, and Rasheed 2007) indicated that 35 to 65 percent of all collected samples were contaminated with fecal and total coliforms and that 85 percent of the tested groundwater samples in Karachi were contaminated with coliforms. Rural areas of Pakistan show similar trends (Mansuri et at. 2018).

Arsenic, Fluoride, and Metals

Between 70 million and 100 million people in Pakistan are at risk from trace metal contamination (Bhowmik et al. 2015; Raza et al. 2017). Studies of trace metal contamination of surface water and groundwater are limited. Arsenic and iron contamination of drinking water sources in Pakistan is largely because of natural geogenic sources that are related to the hydrogeology and groundwater chemistry (Azizullah et al. 2011). Fluoride contamination of groundwater in some areas of Pakistan is also attributable to geogenic sources of the element, though the mechanisms for chemical release of fluoride into groundwater and its chemical stability differ from those of arsenic.

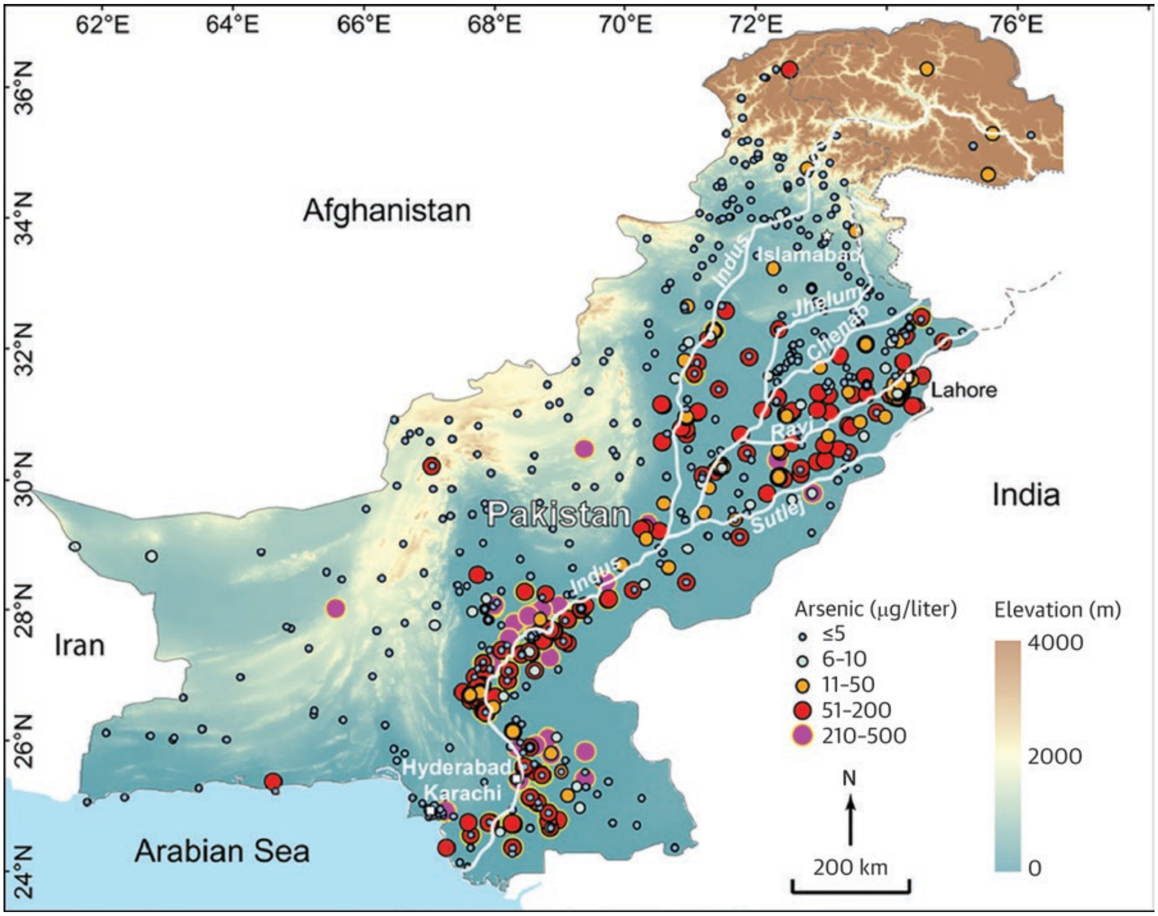
Among the common trace elements studied in Pakistan, arsenic has received the most attention regarding water quality and human health. This is because a large number of people are exposed to arsenic-contaminated water, and the health effects of arsenic at even low concentrations are serious.

Naturally occurring arsenic in aquifer sediments is released into groundwater as groundwater redox conditions change. Using a data set of nearly 1,200 groundwater quality samples throughout Pakistan, Podgorski et al. (2017) found dissolved arsenic concentrations in groundwater in the Indus basin ranging from less than 5 to 500 micrograms per liter. Many of the higher values of more than 50 micrograms per liter are clustered along the Indus River and its tributaries (map 3.14). Elevated arsenic concentrations (more than 200 micrograms per liter) were measured primarily in the southern half of the Indus plain. Of the 1,184 samples, 785 had arsenic concentrations that exceeded the WHO guideline of 10 micrograms per liter (WHO 2017).

A study that conducted field testing of more than 30,000 wells across the Punjab of India and Pakistan (van Geen et al. 2019) found arsenic to be at greatest concentrations in the flood plains of the Ravi River and mostly of concentrations below concern in other parts of the study area.

In studies on the origin of arsenic in Tando Allahyar in Sindh, Naseem and McArthur (2018) indicated that arsenic contamination in groundwater arises from the chemical reduction of iron oxyhydroxides, a process that may largely be driven by microbial reduction of organic matter. The prediction of arsenic

MAP 3.14. **Arsenic Concentrations Measured in Pakistan Groundwater**

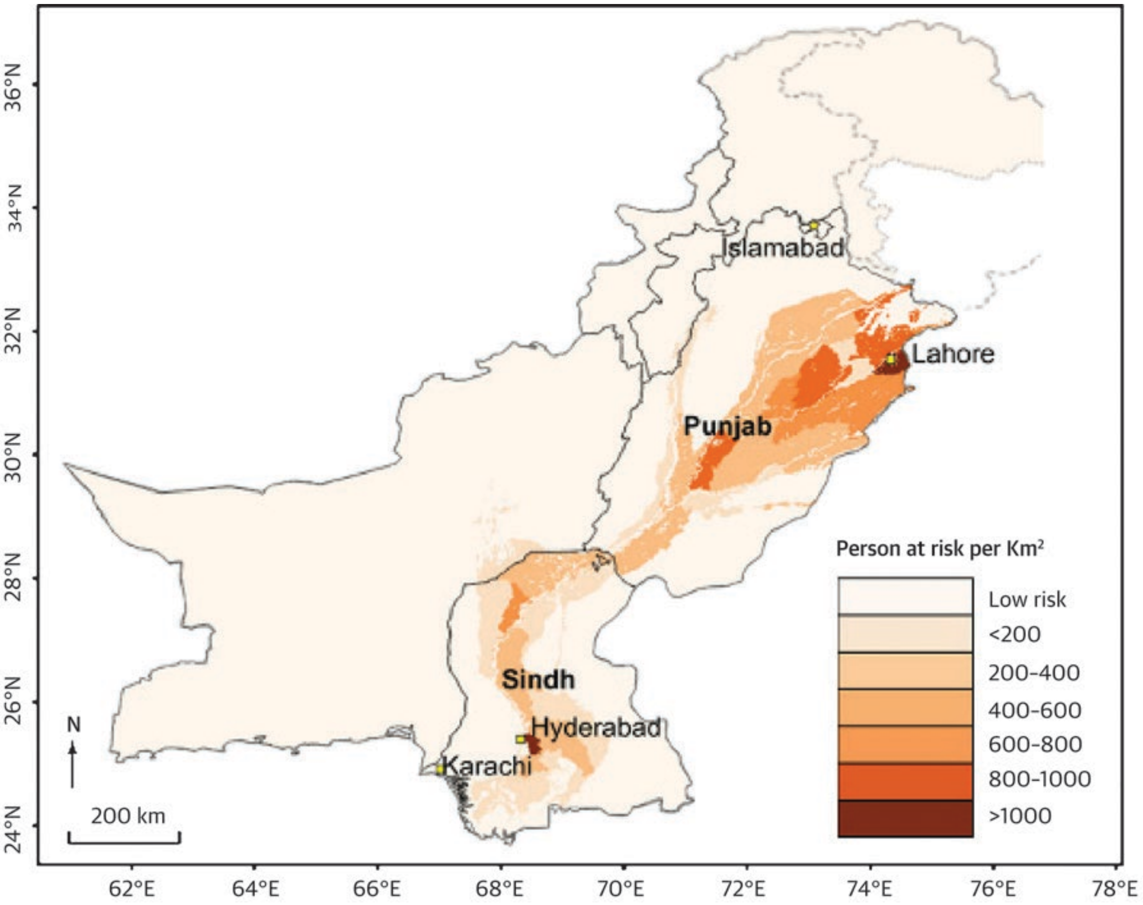


Source: After Podgorski et al. 2017.
Note: Arsenic exceeds the World Health Organization guideline of 10 micrograms per liter in many parts of the Indus plain.

concentrations based on geological information alone is difficult because groundwater chemistry and the presence of organic matter are significant controls. This complexity in turn highlights the utility of reliable empirical data on groundwater quality.

The density of population at risk from high levels of arsenic in groundwater using the WHO guideline of 10 micograms per liter in map 3.15 indicates hotspots around Lahore and Hyderabad. However, there are elevated risks in the doabs of Punjab, southern Punjab, and northern Sindh and along the river where population densities are higher. Studies by Raza et al. (2017) indicated high dissolved arsenic concentrations in surface water and groundwater in Punjab and Sindh provinces. Their study on groundwater quality reported average arsenic levels of 80 micrograms per liter for Karachi, 60.2 micrograms per liter for Sehwan, and 0.002 micrograms per liter for Tharparkar. Samples from Karachi and Sehwan exceeded the WHO guideline of 10 micrograms per liter for drinking water. Studies by PCRWR (Tahir, Rasheed, and Imran 2010) indicated the most widespread trace metal in Sindh was arsenic with concentrations

MAP 3.15. Density of Population at Risk of High Levels of Arsenic in Groundwater



Source: Podgorski et al. 2017.

Note: Risk is for persons predicted to be exposed to arsenic in excess of the World Health Organization guideline of 10 micrograms per liter.

exceeding 200 micrograms per liter in some places. A study by Shahab et al. (2016) indicated arsenic concentrations from 0 to 250 micrograms per liter with a mean value of 22.77 micrograms per liter. The spatial distribution of arsenic in Sindh shows parts of Larkana, Khairpur, Sanghar and Mirpur Khas are within the acceptable range, whereas parts of Dadu, Ghotki, Hyderabad, Jacobabad, Matiari, and Tharparker are affected by higher concentrations. Work conducted in the Tando Allahyar district by Naseem and McArthur (2018) indicate that the presence of anthropogenic contaminants, such as nitrates, will likely influence the trajectory of arsenic concentrations in groundwater. Overextraction and poor groundwater management also influence the release of arsenic into groundwater (MacDonald et al. 2016).

Studies by Rahman et al. (2018) report that fluoride is also present in the groundwater of urban and rural areas of Punjab and Sindh. A review of contamination of groundwater and health risks in Pakistan by Raza et al. (2017) indicated that arsenic and fluoride contamination of groundwater resources is a serious health risk for local communities of Tharparker, Nagarparker, and Umarkot.

Urban Groundwater Quality

Urban groundwater quality poses particular problems. Population growth and increasing urbanization increase volumes of urban wastewater, and leakage from sewerage systems is a serious and growing groundwater pollution risk. Other sources of groundwater pollution in urban areas include industrial and commercial waste discharges, domestic refuse disposal, polluted surface water bodies, such as lakes and canals, and leaks and spills. These sources typically tend to be more concentrated in urban areas, compared with rural areas. Overexploitation of groundwater in urban areas can also cause saltwater intrusion (Ahmad and Kutcher 1992) and the more rapid mobilization of other contaminants. Media reports on the poor status of groundwater in Pakistani cities (declining trends in quality and groundwater level) have led to calls for groundwater regulation and for a pricing mechanism for urban groundwater users, including for commercial entities (for example, Kunbhar 2018).

Siddique et al. (2012) found elevated concentrations of lead in and around the industrial area of the Lyari River (near Karachi) and along the coastal belt. Ul-Haq et al. (2005) found that most of the samples in Malir, Karachi in Sindh, and Charsadda and Risalpur in Khyber Pakhtunkhwa exceeded the WHO guidelines for iron (Fe), manganese (Mn), cadmium (Cd), chromium (Cr), and lead (Pb). Kandhro et al. (2015) conducted a groundwater sample analysis from the city of Nawabshah in Sindh for a range of physicochemical parameters and concluded that 70 percent of groundwater samples were in excess of the WHO maximum permissible limits for some or all parameters. The groundwater of Nawabshah is not safe for drinking, and only four out of 60 water supply scheme samples were found to be acceptable (Kandhro et al. 2015).

In urban Sindh, very few studies have been undertaken on groundwater. Although commercial groundwater use in Karachi is confirmed by the 2018 notice on the requirement for commercial tube wells to be permitted by the Karachi Water and Sewage Board,[13] unregulated growth of tube wells for domestic purposes is suspected and poor groundwater quality is considered inevitable because of domestic effluent, industrial contaminants, and salinity from marine ingress (Khattak and Khattak 2013).

Several studies have found arsenic levels in excess of 50 micrograms per liter (parts per billion) in pumped groundwater in Lahore. For example, Farooqi et al. (2009) found arsenic concentrations ranging from 32 to 1,900 micrograms per liter. The higher arsenic levels were found in groundwater samples at shallow depths (24 to 27 meters) where pH values were also high. Similarly, shallow groundwater samples contained fluoride levels above the WHO drinking water standard of 1.5 milligrams per liter, whereas deeper groundwater samples were free from fluoride contamination. A groundwater quality assessment near Samundri Drain in Faisalabad showed that 90 percent of the samples failed to meet the WHO limits for total dissolved solids (TDS), sodium (Na), potassium (K), choride (Cl) and sulphate (SO_4) (Nasir et al. 2016).

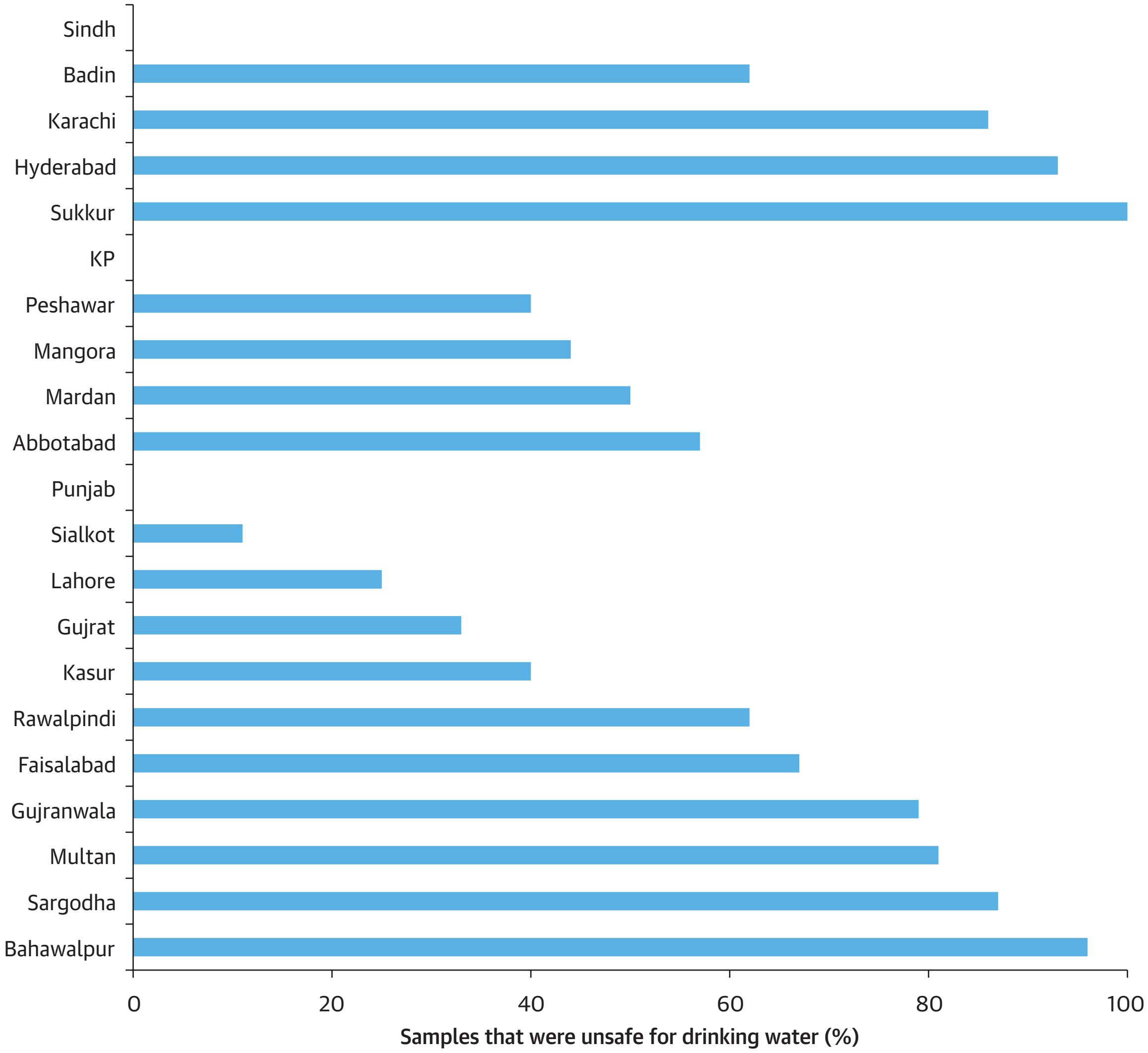
A study of groundwater quality in Rawalpindi revealed that samples from 50 percent of the 220 tube wells serving the city were affected by bacteriological contamination, compared with 33 percent in 2003 (Ul-Haq, Cheema, and Ahmed 2007). It appears that the 0.545 million cubic meters per day of untreated wastewater carried from Islamabad and Rawalpindi by the Nullah Lai and Korang River may have contaminated parts of the aquifer on which Rawalpindi relies.

A study by PCRWR (Kahlown, Tahir, and Rasheed 2007) covering 23 cities found 89 percent of the groundwater throughout the country has a drinking water quality outside the recommended safe limits for human consumption. A subsequent PCRWR nationwide drinking water quality survey carried out in 2015-16 (Imran et al. 2016) found that the groundwater used as the main source of drinking water in Punjab's major cities and towns was unsafe for drinking, according to the National Standards for Drinking Water Quality (Government of Pakistan 2008) as shown in figure 3.17. The results show the unsafe samples in Sindh ranged from 60 percent in Badin to 100 percent in Sukkur. In Khyber Pakhtunkhwa, the range varied from 40 to 60 percent, and in Punjab, the unsafe samples varied from about 11 percent in Sialkot to 96 percent in Bahawalpur (Imran et al. 2016). This shows only modest improvement in some places by comparison to the previous study reported by Kahlown, Tahir and Rasheed (2007).

The groundwater quality in Lahore is reported to be deteriorating as untreated municipal waste from the city continues to be discharged into the nearby Ravi River. As the city has become more developed, recharge from previously agricultural areas has reduced (as a result of the change of land use from agriculture to urban). The Ravi River is now estimated to contribute more than 80 percent of the recharge to the groundwater system (Qureshi and Sayed 2014), resulting in increased levels of pollution in the Lahore aquifer. Industries (textiles, chemical, paper, poultry, dairies, tanneries, and pharmaceuticals) also discharge untreated wastewater into the Lahore Canal running through the city, which can also be drawn into the aquifer as groundwater is pumped. At the district level, the water quality analysis by PCRWR showed 85 percent of the 119 collected samples were found to be unsafe for drinking water (Tahir et al. 2011).

The health risk of poor groundwater management is concentrated in major cities because millions of people depend on the same water supply. With a projected increase in urban population of 140 percent by 2050, groundwater quantity and quality will be the major management challenge, with potential for unrest and conflict.

FIGURE 3.17. **Percent of Samples That Were Unsafe for Drinking Water in Sindh, KP, and Punjab, 2015–16**



Source: Imran et al. 2016.
Note: KP = Khyber Pakhtunkhwa.

Notes

1. The Kharif cropping season (July to October) is during the monsoon, and the Rabi cropping season (October to March) is in winter.
2. This part of Balochistan receives water from the Indus basin system through the Guddu and Sukkur barrages located in Sindh. The Pat Feeder Canal offtakes from the Guddu Barrage, and the Kirthar Branch of the North Western Canal offtakes from the Sukkur Barrage and provides irrigation water for the Nasirabad and Jafarabad districts of Balochistan.
3. Mostly in the eastern part of Tharparkar district.
4. A. L. Qureshi, Mehran University of Engineering and Technology, Jamshoro, Sindh. Email to author 11 Jun 2019.
5. EC is a proxy measure for the concentration of dissolved salts (salinity) in water. Conversion depends on many factors. For this report, the following approximation may be assumed:

   TDS (mg/l) = (EC (μS/cm) × 0.64

6. A. R. Khilji, engineer, Balochistan Irrigation Department. Email to author 27 Jun 2019.

7. The temperature and rainfall data presented here were obtained from National Oceanic and Atmospheric Administration (NOAA) (www.ncdc.noaa.usgs).

8. The daily global potential evapotranspiration (ET) is calculated from climate data from Global Data Assimilation System (GDAS) analysis fields. The GDAS data are generated every six hours by NOAA, and the fields used as input including air temperature, atmospheric pressure, wind speed, relative humidity, and solar radiation. The data provide spatial and temporal pictures. Processed data for Rabi that were available had significant errors and are not shown.

9. By Dr. J. Punthakey, Australian Center for International Agriculture Research (ACIAR) project on improving groundwater management to enhance agriculture and farming livelihoods.

10. SAR is a measure of the relative concentrations of dissolved sodium, calcium, and magnesium ions in irrigation water. Water with a high SAR can cause soils to lose structure.

11. RSC is a measure of alkalinity hazard in irrigation water.

12. DRASTIC refers to a methodology for determining intrinsic groundwater vulnerability, utilizing seven hydrogeological parameters: depth to water table (D), net recharge (R), aquifer material (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity (C).

13. See *The Sindh Government Gazette*, September 28, 2018, at http://www.kwsb.gos.pk/SitePdfFiles/GAZETTE28.pdf.

References

ACE (Associated Consulting Engineers), EGC (Engineering General Consultants), and SMEC International. 2011. Nationwide Study of Groundwater Availability and Conjunctive Management. Volume 1. Ministry of Water and Power, Project Management and Policy Implementation Unit, Government of Pakistan. Lahore.

Ahmad, M., and G. P. Kutcher. 1992. “Irrigation Planning with Environmental Considerations. A Case Study of Pakistan’s Indus Basin.” Technical Paper No. 166, World Bank, Washington DC.

Alamgir, A., M. A. Khan, J. Schilling, S. S. Shaukat, and S. Shahab. 2016. “Assessment of Groundwater Quality in the Coastal Area of Sindh Province, Pakistan.” *Environmental Monitoring and Assessment* 188 (2): 78. https://doi.org/10.1007/s10661-15-5061-x.

Amir, P., and Z. Habib. 2015. “Estimating the Impacts of Climate Change on Sectoral Water Demand in Pakistan.” ACT Report, Action on Climate Today, Nottinghamshire, U.K. Accessed March 2019. https://cyphynets.lums.edu.pk/images/Readings_concluding.pdf.

Azizullah, A., M. N. K. Khattak, P. Richter, and D. P. Häder. 2011. “Water Pollution in Pakistan and Its Impact on Public Health—A Review.” *Environment International* 37 (2): 479-97. https://www.sciencedirect.com/science/article/pii/S0160412010002060.

Basharat, M., Tariq, A. 2015. “Groundwater modelling for need assessment of command scale conjunctive water use for addressing the exacerbating irrigation cost inequities in LBDC irrigation system, Punjab, Pakistan.” Sustainable Water Resources Management. 1, 41-55. https://doi.org/10.1007/s40899-015-0002-y

BGS (British Geological Survey). 2015. “Groundwater Resources in the Indo-Gangetic Basin: Resilience to Climate Change and Abstraction.” Open Report No. OR/15/047, BGS, Keyworth, U.K.

Bhowmik, A. K., A. Alamdar, I. Katsoyiannis, H. Shen, N. Ali, S. M. Ali, H. Bokhari, R. B. Schäfer, S. A. M. Akber, and S. Eqani. 2015. “Mapping Human Health Risks from Exposure to Trace Metal Contamination of Drinking Water Sources in Pakistan.” *Science of the Total Environment* 538: 306-16.

Bonsor, H. C., A. M. MacDonald, K. M. Ahmed, W. G. Burgess, M. M. Basharat, R. C. Calow, A. Dixit, S. S. D. Foster, K. Gopal, D. J. Lapworth, M. Moench, A. Mukherjee, M. S. Rao, M. Shamsudduha, R. G. Smith, R. G. Taylor, J. Tucker, F. van Steenbergen, S. K. Yadav, and A. Zahid. 2017. “Hydrogeological Typologies of the Indo-Gangetic Basin Alluvial Aquifer, South Asia.” *Hydrogeology Journal* 25 (5): 1377-406.

Chandio, B. A., M. Abdullah, and M. A. Tahir. 1999. “Drinking Water Quality and Standardization in Pakistan” in Proceedings of the National Workshop on Quality of Drinking Water, Islamabad, March 7, 1998. https://www.ircwash.org/sites/default/files/242-15920.pdf

Chaudhry, M. N., S. A. Ahmed, and A. Mateen. 1999. “Some Postulates of Tectonomagmatism, Tectonostratigraphy and Economic Potential of Kirana - Malani Basin: Implications for Occurrence of Petroleum.” *Pakistan Journal of Hydrocarbon Research* 11: 29-35.

Chaudhry, Q. U. Z. 2017. “Climate Change Profile of Pakistan”. Manila, Philippines: ADB. DOI: http://dx.doi.org/10.22617/TCS178761

Custodio, Emilio. 2013. “Trends in Groundwater Pollution: Loss of Groundwater Quality and Related Services.” Thematic Paper 1, Groundwater Governance. http://www.groundwatergovernance.org/fileadmin/user_upload/groundwatergovernance/docs/Thematic_papers/GWG_Thematic_Paper_1.pdf

Daud, M. K., M. Nafees, S. Ali, M. Rizwan, A. Bajwa, M. B. Shakoor, M. U. Arshad, S. Ali, S. Chatha, F. Deeba, W. Murad, I. Malook, and S. J. Zhu. 2017. “Drinking Water Quality Status and Contamination in Pakistan. Review Article.” *BioMed Research International* 2017: 18. Accessed April 10, 2019. https://www.hindawi.com/journals/bmri/2017/7908183

Dawn. 2018. “Bottled Water Firms Ordered to Pay Price of Groundwater.” December 4. https://www.dawn.com/news/1449318/bottled-water-firms-ordered-to-pay-price-of-groundwater.

FAO (Food and Agriculture Organisation). 2012. Irrigation in Southern and Eastern Asia in figures. AQUASTAT Survey - 2011 FAO WATER REPORTS. Editor K. FRENKEN, FAO Land and Water Division. 37. Rome. http://www.fao.org/3/i2809e/i2809e.pdf

Farooqi, A., H. Masuda, R. Siddiqui, and M. Naseem. 2009. “Sources of Arsenic and Fluoride in Highly Contaminated Soils Causing Groundwater Contamination in Punjab, Pakistan.” *Environmental Contamination and Toxicology* 56 (4): 693-706. https://link.springer.com/article/10.1007/s00244-8-9239-x.

Friends of Democratic Pakistan. 2012. A Productive and Water-Secure Pakistan: Infrastructure, Institutions, Strategy. A Report of the Water Sector Task Force of the Friends of Democratic Pakistan, Islamabad. https://metameta.nl/wp-content/uploads/2013/11/FoDP-WSTF-Report-Final-09-29-12.pdf

Foster, S., A. Pulido-Bosch, Á. Vallejos, L. Molina, A. Llop, and A. M. MacDonald. 2018. “Impact of Irrigated Agriculture on Groundwater-Recharge Salinity: A Major Sustainability Concern in Semi-Arid Regions.” Hydrogeology Journal 26 (8): 2781-91. https://link.springer.com/article/10.1007/s10040-18-830-2

Fowler, H. J., and D. R. Archer, 2006: Conflicting Signals of Climatic Change in the Upper Indus Basin. Journal of Climate, 19, 4276-4293, https://doi.org/10.1175/JCLI3860.1.

Geyh, M., and D. Ploethner. 2008. “Origin of a Fresh Groundwater Body in Cholistan, Thar Desert, Pakistan.” *Geological Society, London, Special Publications* 288: 99-109.

Government of Pakistan. 2017. National Policy Dialogue on Salt-Affected Soils, Islamabad, March 7. www.fao.org/pakistan/news/detail-events/en/c/522681/.

Government of Pakistan. 2008. National Standards for Drinking Water Quality (NSDWG). Pakistan Environmental Protection Agency, Ministry of Environment. Islamabad.

Greenman, D. W., W. V. Swarzenski, and G. D. Bennett. 1967. “Ground-water Hydrology of the Punjab, West Pakistan with Emphasis on Problems Caused by Canal Irrigation.” Geological Survey Water-Supply Paper 1608-H, U.S. Department of the Interior, Washington, DC.

Hunting Technical Services Ltd and Sir Mott MacDonald and Partners. 1965. Lower Indus Report, Physical Resources-Groundwater, Volume 6, Supplement 6.1.3, 4 and 5. West Pakistan Water and Power Development Authority.

Imran, S., K. Anwar, L. N. Bukhari, and M. Ashraf. 2016. *Water Quality Status of Major Cities of Pakistan 2015-16*. Islamabad: Pakistan Council of Research in Water Resources.

IWASRI (International Waterlogging and Salinity Research Institute). 2011. “Groundwater Management: Recharge Potential and Governance. Irrigation System Issues and Groundwater Governance.” IWASRI Technical Report 295, Water and Power Development Authority, Lahore, Pakistan.

Kahlown, M. A., M. A. Tahir, and H. Rasheed. 2007. *Water Quality Status of Pakistan (5th Technical Report 2005-2006)*. Islamabad: Pakistan Council of Research in Water Resources. http://www.pcrwr.gov.pk/Publications/Water%20Quality%20Reports/Water%20Quality%20Monitoring%20Report%202005-06.pdf

Kandhro, A. J., A. M. Rind, A. A. Mastoi, K. F. Almani, S. Meghwar, M. A. Laghari, and M. S. Rajpout. 2015. “Physico-Chemical Assessment of Surface and Groundwater for Drinking Purpose in Nawabshah City, Sindh, Pakistan.” *American Journal of Environmental Protection*.4 (1): 62-9.

Khan, A. D., N. Iqbal, M. Ashraf, and A. A. Sheikh. 2016. *Groundwater Investigations and Mapping in the Upper Indus Plain*. Islamabad: Pakistan Council of Water Resources Research.

Khan, M. A. 1978. *Hydrological Data, Rechna Doab, Volume I.* Lahore, Pakistan: Project Planning Organization (NZ) and Pakistan Water and Power Development Authority.

Khan, S., F. Haq, and K. Saeed. 2012. "Pollution Load in Industrial Effluent and Groundwater Due to Marble Industry in District Buner, Khyber Pakhtunkhwa, Pakistan." *International Journal of Recent Scientific Research* 3 (5), pp366-368. Accessed May 2019. http://www.recentscientific.com.

Khattak, M. I., and M. I. Khattak. 2013. "Groundwater Analysis of Karachi with Reference to Adverse Effect on Hukn Health and Its Comparison with Other Cities of Pakistan." Journal of Environmental Science and Water Resources 2 (11): 410–18.

Kunbhar, Z. (2018). Groundwater woes of Sindh. Daily Times. online. https://dailytimes.com.pk/299286/groundwater-woes-of-sindh/

Lashari, B. K., H. Ursani, M. Basharat, F. Steenbergen, M. Ujan, Z. Khero, N. E. Memon, S. Esin, A. W. Sheikh, M. A. H. Mahar, A. Bashir, G. Channar, A. Hussain, M. A. Mangrio, S. M. Kori, G. H. Wagan, S. N. Chandio, A. Muhammed, M. Ahmed, A. A. Detho, A. A. Mehmood, K. Ali, A. Jawad, A. Wahid, S. H. Memon, A. Mallah, C. Borgia, and S. Gohar 2015. "The Promise of Conjunctive Management of Surface and Groundwater in Sindh." Shared Discussion Paper. *Meta Meta Groundwater Magazine*, January, http://metameta.nl/wp-content/uploads/2017/02/gwmagazines1_conjunctive_Sindh_LQ.pdf

MacDonald, A. M., H. C. Bonsor, K. M. Ahmed, W. G. Burgess, M. Basharat, R. C. Calow, A. Dixit, S. S. D. Foster, K. Gopal, D. J. Lapworth, R. M. Lark, M. Moench, A. Mukherjee, M. S. Rao, M. Shamsudduha, L. Smith, R. G. Taylor, J. Tucker, J., F. van Steenbergen, and S. K. Yadav. 2016. "Groundwater Quality and Depletion in the Indo-Gangetic Basin Mapped from in Situ Observations." *Nature Geoscience* 9: 762.

Mahmood, K., Rana, A.D., Tariq, S., Kanwal, S., Ali, R., Ali, A. H., Tahseen, T. (2013). "Groundwater Levels Susceptibility to Degradation in Lahore Metropolitan". Science International (Lahore) 25(1): 123-126. http://www.sci-int.com/pdf/102089200722-123-126-Groundwater%20Levels%20Susceptibility%20_revised_%20Space%20Science%20Khalid.pdf

Mahessar, A. A., A. L. Qureshi, H. Ursani, I. Tunio, B. Kandhro, and S. A. Memon, 2017. "Environmental Concerns for Water Consumption from Polluted Water Bodies in Watershed Area of Sindh Province." *Journal of Pollution Effects and Control* 5 (4): 204. https://www.researchgate.net/profile/Tunio_Imran_Aziz/publication/322679813_Environmental_Concerns_for_Water_Consumption_from_Polluted_Water_Bodies_in_Watershed_Area_of_Sindh_Province/links/5ad4fe900f7e9b285936ac17/Environmental-Concerns-for-Water-Consumption-from-Polluted-Water-Bodies-in-Watershed-Area-of-Sindh-Province.pdf.

Malik, M. A., M. Azam, and A. Saboor. 2010. Water Quality Status of Upper KPK and Northern Areas of Pakistan. Islamabad: Pakistan Council of Research in Water Resources

Mansuri, Ghazala, Mohammad Farhanullah Sami, Muhammad Ali, Hang Thi Thu Doan, Bilal Javed, and Priyanka Pandey. 2018. "When Water Becomes a Hazard: A Diagnostic Report on The State of Water Supply, Sanitation and Poverty in Pakistan and Its Impact on Child Stunting" (English). WASH Poverty Diagnostic Series, World Bank, Washington, DC. http://documents.worldbank.org/curated/en/649341541535842288/When-Water-Becomes-a-Hazard-A-Diagnostic-Report-on-The-State-of-Water-Supply-Sanitation-and-Poverty-in-Pakistan-and-Its-Impact-on-Child-Stunting.

Memon, M., M. S. Soomro, M. S. Akhtar, and K. S. Memon. 2011. "Drinking Water Quality Assessment in Southern Sindh (Pakistan)." *Environmental Monitoring and Assessment* 177: 39–50.

Mueller, W., D. Ploethner, and K. M. Ashraf. 1991. "Groundwater Investigations in Desert Areas of Pakistan, Volume II A: Results of Hydrogeological Investigations, Annexures." Technical Cooperation Project, commissioned by Federal Institute for Geosciences and Natural Resources (Bundesanstalt fuer Geowissenschaften und Rohstoffe), Hannover, Federal Republic of Germany, for Water and Power Development Authority Hydrogeology Directorate, Lahore, Pakistan.

Naseem, S., V. Husain, and S. Bano. 2018. "Origin of Salinity and Other Constituents in Indus Deltaic Plain Groundwater, Thatta District, Pakistan." *Journal of Coastal Research* 34 (4): 883–91.

Naseem, S., and J. M. McArthur. 2018. "Arsenic and Other Water Quality Issues Affecting Groundwater, Indus Alluvial Plain, Pakistan." *Hydrological Processes* 32 (9): 1235–53. https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.11489.

Nasir, A., M. S. Nasir, I. Shauket, S. Anwar, and I. Ayub. 2016. "Impact of Samanduri Drain on Water Resources of Faisalabad." *Advances in Environmental Biology* 10: 155-160. Accessed February 12, 2019. https://www.researchgate.net/publication/298699529_Impact_of_Samanduri_Drain_on_Water_Resources_of_Faisalabad.

Osborne, Thomas H., Seamus A. Ward, Kazi M. Ahmed, and Joanne M. Santini. 2018. "Reservoirs of Faecal Indicator Bacteria in Well-Head Hand Pumps in Bangladesh." *Journal of Water Health* 16 (3): 487–90. https://doi.org/10.2166/wh.2018.042.

Podgorski, J. E., S. A. M. A. S. Eqani, T. Khanam, R. Ullah, H. Shen, and M. Berg. 2017. "Extensive Arsenic Contamination in High-pH Unconfined Aquifers in the Indus Valley." *Science Advances* 3 (8): e1700935. https://advances.sciencemag.org/content/3/8/e1700935.abstract.

Post, V. E. A., Houben, G. J., & van Engelen, J. 2018. What is the Ghijben-Herzberg principle and who formulated it? Hydrogeology Journal, 26(6), 1801-1807.

Punthakey JF, Culas R, Baig I, Khan MR, Riaz M, Javed M, and Hassan GZ. 2016 SRA for handover and training of surface-groundwater and econometric models to end users in Pakistan. Report to ACIAR. Ecoseal Consulting Report. CR 2016.141, 88p.

Punthakey, J. F., M. R. Khan, M. Riaz, M. Javed, G. Zakir, M. Usman, M. Amin, R. N. Ahmad, J. Blackwell, R. Culas, I. A. Baig, and E. Christen. 2015. *Optimising Canal and Groundwater Management to Assist Water User Associations in Maximizing Crop Production and Managing Salinisation in Pakistan: Assessment of Groundwater Resources for Rechna Doab, Pakistan.* Report to Australian Center for International Agricultural Research (ACIAR), Ecoseal - Water Resources Management.

Punthakey, J. F., A. A. Khowaja, and S. A. Prathapar. 1997. *Health and Irrigation Management in Sindh - Issues and Research Priorities.* Consulting Report for International Irrigation Management Institute, Pakistan.

Punthakey, Jehangir; Schmid, Wolfgang; Hodgson, Geoff; Ahmad, Mobin; Podger, Geoff; Basharat, Muhammad. Regional groundwater model of the Indus Basin, Pakistan: Hydrogeological analysis of borelogs. Australia: CSIRO; 2017. https://doi.org/10.4225/08/59a5b9cd1199d.

Qureshi, A. & Sayed, A., H. (2014). Situation Analysis of the Water Resources of Lahore: Establishing a Case for Water Stewardship. WWF-Pakistan.

Qureshi AS, Shah T, Akhtar M (2003) The groundwater economy of Pakistan. IWMI working paper no 64, International Water Management Institute, Colombo, Sri Lanka, 23 pp

Rahman, Z. U., B. Khan, and I. Ahmada. 2018. "A Review of Groundwater Fluoride Contamination in Pakistan and an Assessment of the Risk of Fluorosis." Fluoride 51 (2): 171-81.

Raza, Maimoona, Fida Hussain, Jin-Yong Lee, Muhammad Shakoor, and Kideok Kwon. 2017. "Groundwater Status in Pakistan: A Review of Contamination, Health Risks, and Potential Needs." *Critical Reviews in Environmental Science and Technology* 47 (18): 1713-62.

Riaz, U., Z. Abbas, Q. uz Zaman, M. Mubashir, M. Jabeen, S. A. Zulqdar, Z. Javed, S. ur Rehman, M. Ashraf, and M. J. Qamar. 2018. "Evaluation of Ground Water Quality for Irrigation Purposes and Effect on Crop Yields: A GIS Based Study of Bahawalpur." *Pakistan Journal of Agricultural Research.* 31(1): 29-36. http://researcherslinks.com/current-issues/Evaluation-of-Ground-Water-Quality-for-Irrigation/24/1/1149/html.

Shahab, A., Q. Shihua, A. Rashid, F. Hasan, and M. T. Sohail. 2016. "Evaluation of Water Quality for Drinking and Agricultural Suitability in the Lower Indus Plain in Sindh Province, Pakistan." *Polish Journal of Environmental Studies* 25 (6): 2563-67.

Shahab, Asfandyar, Qi Shihua, Saeed Rad, Souleymane Keita, Majid Khan, and Syed Adnan. 2019. "Groundwater Vulnerability Assessment Using GIS-Based DRASTIC Method in the Irrigated and Coastal Region of Sindh Province, Pakistan." *Hydrology Research* 50 (1): 319-38

Siddique, A., N. A. Zaigham, S. Mohiuddin, M. Mumtaz, S. Saied, and K. A. Mallick. 2012. "Risk Zone Mapping of Lead Pollution in Urban Groundwater." *Australian Journal of Basic and Applied Sciences* 8: 91-96.

Soomro, Faisal Yousuf, Tahir Rafique, Greg Michalski, Syed Ali, and Shahid Naseem. 2017. "Occurrence and Delineation of High Nitrate Contamination in the Groundwater of Mithi Sub-District, Thar Desert, Pakistan." *Environmental Earth Sciences* 76: 355.

Tahir, M., M. Akram, F. Ul-Hassan, and M. Farouq. 2011. *Technical Assessment of Water Supply Schemes.* Islamabad: Pakistan Council of Research in Water Resources.

Tahir, M. A., H. Rasheed, and S. Imran. 2010. *Water Quality Status in Rural Areas of Pakistan.* Islamabad: Pakistan Council of Research in Water Resources.

Ul-Haq, I., W. A. Cheema, and C. N. Ahmed. 2007. "Multifaceted Ground Water Quality and Recharge Mechanism Issues in a Megacity (Rawalpindi, Pakistan), and Mitigation Strategies, Securing Groundwater Quality in Urban and Industrial Environments." 6th International IAHS Ground Water Quality Conference, Fremantle, Western Australia, December 2-7.

Ul-Haq, M., R. A. Khattak, H. K. Puno, M. S. Saif, and K. S. Memon. 2005. "Surface and Ground Water Contamination in NWFP and Sindh Provinces with Respect to Trace Elements." *International Journal of Agriculture and Biology.* 7(2): 214-7. http://www.ijab.org.

van Geen, A., A. Farooqi, A. A. Kumar, J. A. Khattak, N. Mushtaq, I. Hussain, T. Ellis, and C. K. Singh. 2019. "Field Testing of over 30,000 Wells for Arsenic across 400 Villages of the Punjab Plains of Pakistan and India: Implications for Prioritizing Mitigation." *Science of The Total Environment* 654: 1358-63.

Waqar, J. A., A. S. Qureshi, and N. Ali. 2002. "Conjunctive Water Management in the Rechna Doab: An Overview of Resources and Issues." Working Paper 48, International Water Management Institute, Lahore, Pakistan.

The White House. 1964. *Report on Land and Water Development on the Indus Plain.* Washington, DC: Department of the Interior Panel on Waterlogging and Salinity in West Pakistan.

USGS n.d. Figure from US Geological Survey website accessed November 2019 at: https://water.usgs.gov/ogw/gwrp/saltwater/salt.html; modified from Cooper, H. H., 1964, A hypothesis concerning the dynamic balance of freshwater and saltwater in a coastal aquifer: U.S. Geological Survey Water-Supply Paper 1613-C, p. 1-12.

WHO (World Health Organization). 2017. *Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First Addendum.* Geneva: WHO.

Young, W. J., A. Anwar, T. Bhatti, E. Borgomeo, S. Davies, W. R. Garthwaite, E. Gilmont, C. Leb, L. Lytton, I. Makin, and B. Saeed. 2019. “Pakistan: Getting More from Water.” Water Security Diagnostic, World Bank, Washington, DC.

Yu, W., Y. C. Yang, A. Savitsky, D. Alford, C. Brown, J. Wescoat, D. Debowicz, and S. Robinson. 2013. *The Indus Basin of Pakistan: The Impacts of Climate Risks on Water and Agriculture.* Washington, DC: World Bank. doi:10.1596/978-0-8213-9874-6.

Chapter 4
The State of Groundwater Management

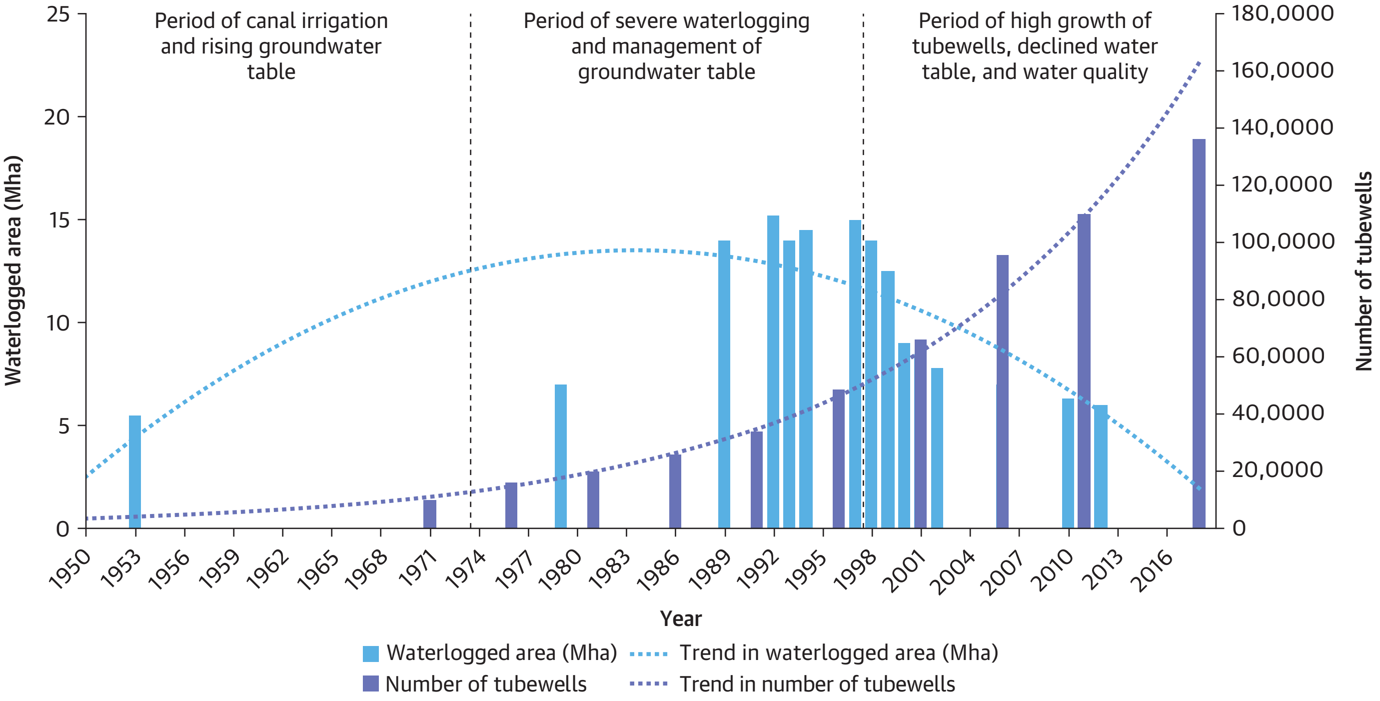
Key Points

- Pakistan's National Water Policy 2018 is a foundation for groundwater management in Pakistan's Indus basin. The policy contains several specific objectives for groundwater, mostly related to improving knowledge of groundwater resources and identifying and managing groundwater quality.
- Support in the legal framework for groundwater management is fragmented and more limited than in some other groundwater-dependent countries.
- A patchwork of national, provincial, and local institutions undertakes scattered activities related to groundwater management, but coordination is lacking, and the collection and integration of groundwater data remains poor. Groundwater monitoring is patchy and the data unreliable.
- The lack of reliable data on groundwater levels, abstraction volumes, salinity, and broader water quality parameters makes policy formulation more difficult, hindering action and preventing the optimal use of resources.
- Groundwater is critically important to Pakistan, and the burden of poorly managed groundwater, including salinization, poor water quality, falling water tables, and waterlogging will continue to worsen.

Introduction

The development of a significant groundwater resource in the Indus basin as a result of the extensive irrigation system, and the subsequent challenges of waterlogging and groundwater depletion, have been discussed in earlier chapters. A historical summary of the development of the resource and management response is depicted in figure 4.1. In this chapter, key policies, plans, legislation, and institutions are highlighted to identify what is being done to manage groundwater in Pakistan's Indus basin.

FIGURE 4.1. Historical Perspective of Groundwater Development and Management in the Pakistan's Indus Basin



Source: Original compilation.
Note: Mha = million hectare.

Policy

Policies relevant to water exist at both national and provincial levels.

National Water Policy

Pakistan's National Water Policy 2018 provides the overarching policy foundation for groundwater management in the Indus basin. The content of the policy is the result of nearly two decades of discussions. In 2002, the first draft of a national water policy was prepared, after which the document underwent reviews and several changes to secure consensus among the provinces and the federal government. During these years, there were several related policy developments and a general trend toward an increasing role for provincial governments. In 2010, the Eighteenth Amendment to Pakistan's Constitution signaled this shift toward greater provincial autonomy.

Two other relevant policy documents informed the National Water Policy: the National Sustainable Development Strategy 2012 and, in 2014, the Pakistan Vision 2025. These documents recognized the problems of unregulated pumping, depletion of groundwater, water pollution from municipal and industrial sources, low-quality drinking water, and poor sanitation coverage, as well as associated health hazards. The final version of the National Water Policy incorporated these developments and was published by the newly created Ministry of Water Resources and approved by the Council of Common Interests in April 2018. The policy was accompanied by the Pakistan Water Charter—a high-level commitment from the prime minister of Pakistan and the chief ministers of each province to prioritize improving water management.

The National Water Policy has several parts that are specific to groundwater management. The overall objective of the policy is to provide a framework and a set of principles on which provincial governments can plan and implement water conservation, development, and management. In its guiding principles, the policy calls for the adoption of integrated water resource management practices and explicitly notes the need to strengthen institutional and management capacity for water management at all levels. The policy contains a dedicated chapter on groundwater with eight specific policy objectives, across which are two main themes: (a) a recognition of the need to improve knowledge of available groundwater resources and uses and (b) a recognition of the need to identify and manage groundwater quality issues. Groundwater issues also figure prominently in several sectoral dimensions of the policy. For example, chapter 10 deals with irrigation and calls on provinces to study the implications of irrigating with marginal-quality groundwater. Waterlogging and salinity management are also discussed. Falling groundwater levels are mentioned as a priority concern in the chapter on drinking water. The policy affirms the role and responsibility of provincial governments in managing groundwater and calls for the establishment of a new "groundwater water authority" in each province to oversee the regulation of groundwater.

Provincial Policies

Each province is at a different stage in the development of a water policy framework. Balochistan and Punjab have led the way with recent developments. The government of Punjab approved its water policy in December 2018 and in December 2019 passed the Punjab Water Act 2019. The policy recognizes groundwater as a critical resource for development and dedicates a high-level policy objective to managing groundwater abstraction for sustained production and reduced land degradation and health hazards and "to balance recharge levels through regulation, reallocation of canal allowances, induced recharge and monitoring." Groundwater is the focus of subsections of the policy aimed at enhancing water availability and improving water quality, and it also features in sectoral policy objectives related to drinking water, drought management, water conservation, waterlogging and salinity control. Balochistan's Integrated Water Resources Management Policy 2006 contains a similar emphasis, particularly the issues of groundwater mining and the falling water table. Of the three overdrawn basins in Balochistan, the Nari and Zhob rivers are part of the Indus basin. In these basins, the policy imposes a ban on installation of new agricultural tube wells, restricting it to the replacement of wells that have gone dry.

Sindh and Khyber Pakhtunkhwa provinces are still in the process of drafting specific water policies, but some key elements can already be found in policy documents from related sectors. For example, the Sindh Agriculture Policy 2018 calls for regulating and controlling groundwater resources. Under the Agriculture Policy's key action areas, the government of Sindh will legislate for more sustainable use of groundwater and the control of “pollution ‘hotspots’ such as industrial areas where chemical and other effluent is dumped into soil and water, and in highly concentrated peri-urban dairy production areas.” Sindh has already established a steering committee and has undertaken preparation of background studies to support the water policy. Although Khyber Pakhtunkhwa is in the process of preparing a specific water policy, some water-related elements are already included in the province’s Drinking Water Policy 2015 and Climate Change Policy 2016. Although groundwater is only a small component, the Climate Change Policy includes two specific policy measures on groundwater: It calls for the promotion of sustainable groundwater exploitation, and it calls for protecting groundwater “through management and technical measures like regulatory frameworks, water licensing, slow action dams, artificial recharge especially for threatened aquifers.” The Drinking Water Policy requires conserving groundwater, protecting water quality, and enhancing the capacity of relevant institutions.

Development Plans

Development and resource allocation in Pakistan are guided through five-year development plans at the national and provincial levels (see appendix C). Subsidiary annual development plans then facilitate implementation of these five-year plans, which draw on national and provincial policy to specify investment and allocation of funds. Since 1955, the government of Pakistan has issued 11 five-year plans at the national level, and water—and specifically groundwater—has featured in several of them. For example, the second five-year plan targeted waterlogging and the development of major infrastructure for interbasin transfer under the Indus Waters Treaty of 1960. The third and fourth five-year plans emphasized water conservation, waterlogging, and salinity. The sixth and seventh five-year plans sought to provide stakeholder mandates to improve water management. The sixth five-year plan also focused on water conservation through watercourse lining. Water sector allocations in these plans were aligned with the requirements of counterpart financing for megadevelopment projects that received significant external funds. These included several waterlogging, salinity control, and groundwater management projects.

The 2019-20 national annual development plan under the twelfth five-year plan (the full text of which is still to be published) contains references to groundwater management, and it recognizes the new National Water Policy. The plan indicates integrated water resources management as an overarching approach though, overall, groundwater is a relatively small component of the plan. Groundwater recharge is among the priority programs to be funded, linked to both water resources development and climate change and environment. Groundwater studies are among the priority projects for the Geological Survey of Pakistan. Sustainable groundwater management in Balochistan is listed among priority projects under science and technology.

Groundwater management can also be part of provincial development plans. For example, the government of Punjab’s Annual Development Program 2019-20 includes priority sectoral strategies aimed at developing and practicing “holistic approaches to optimize surface and groundwater use efficiencies” and mitigating “environmental degradation and groundwater mining.” It specifically allocates funding to a groundwater recharge project under broader efforts at survey, investigation, and research. Sindh’s Annual Development Plan 2019-20 also refers to groundwater-related programs, including a budget line item for groundwater investigation and mapping. Similarly, Khyber Pakhtunkhwa's Annual Development Plan includes a line item for an underground water study and a pilot project on artificial aquifer recharge. Balochistan's Annual Development Plan 2019-20 includes allocations for Balochistan's Water Resource Development Project, which also considers groundwater in the river basin and water balance context. Other line items include construction of delay action dams aiming at groundwater recharge and the rehabilitation of *karezes*[1] for reactivation of subsurface flow.

Legal Framework

Like the broader legal framework for overall water resources management, the legal framework for groundwater management in the Indus basin is made up of a mixture of national and provincial legislation and common law rules. Overall, the treatment of groundwater is more limited than in some other groundwater-dependent countries. However, there are basic legal provisions already in force at the national and provincial levels that could be used to support improvements in groundwater management. The most significant legislation for groundwater management in the Indus basin is shown in table 4.1.

Legal Authority to Manage Groundwater

The legal authority to manage groundwater resources is provided both by national and provincial legislation. As the foundation, Pakistan's 1973 Constitution divides authority between the national government and the provinces. The Eighteenth Amendment to the Constitution in 2010 started a shift towards decentralization to the provinces. Prior to this amendment, environmental pollution and ecology were enumerated items under a list of subject matters for which the federal and provincial governments

TABLE 4.1. Key Legislation for Groundwater Management in the Indus Basin

National level

- Water and Power Development Authority Act 1958
- Pakistan Council of Research in Water Resources Act 2007

Punjab province

- Punjab Water Act 2019
- Punjab Irrigation and Drainage Authority Act 1997 (repealed November 2019)
- Punjab Canal and Drainage Act 1873
- Punjab Local Government Act 2019
- Punjab Environmental Protection Act 1997
- Punjab Soil Reclamation Act 1952

Sindh province

- Sindh Water Management Ordinance 2002
- Sindh Local Government Act 2013
- Sindh Environmental Protection Act 2014

Balochistan province

- Balochistan Irrigation and Drainage Authority Act 1997
- Balochistan Groundwater Rights Administration Ordinance 1978
- Balochistan Water and Sanitation Authority Act 1989
- Balochistan Environment Protection Act 2012

Khyber Pakhtunkhwa province

- Khyber Pakhtunkhwa Irrigation and Drainage Authority Act 1997
- Khyber Pakhtunkhwa Integrated Water Resources Management Board Ordinance 2002
- Khyber Pakhtunkhwa Environmental Protection Act 2014

would exercise concurrent jurisdiction.[2] Following the amendment, the only items that remain under concurrent jurisdiction are criminal law, criminal procedure, and evidence. Groundwater and water resources generally are not specifically enumerated in the federal list in the fourth schedule of the constitution, meaning responsibility is left with the provincial governments.

However, under the constitution, two potentially relevant areas still fall within federal jurisdiction: (a) interstate water disputes and (b) policy setting for water and power development as covered by the Water and Power Development Authority Act 1958 and in force before the promulgation of the 1973 Constitution.[3] This latter area is particularly important for the legal authority to manage groundwater. The Water and Power Development Authority Act provides in section 11 that, "[s]ubject to the provisions of any other law for the time being in force, the Authority - (i) shall have control over the - (a) underground water resources of any region in a Province" and "[b]efore the Authority exercises any control under clause (i) of subsection (1), the area over which and the extent to which control is intended to be exercised shall be agreed to and notified by the Government in the official Gazette."

Several provinces have similar provisions. In Punjab, following the November 2019 repeal of the Punjab Irrigation and Drainage Authority Act 1997, the conservation, allocation, and management of water resources in the province (including groundwater) is now the responsibility of the Punjab Water Resources Commission under the Punjab Water Act 2019. The act was passed in December 2019 and allows the government six months to establish the commission. Section 13 of the Balochistan Irrigation and Drainage Authority Act 1997 provides that "the Authority shall have control over all the … underground water resources within the Province;" section 12(e) of the Balochistan Water and Sanitation Authority Act 1989 further provides that the Water and Sanitation Authority has control over groundwater in designated urban areas. A similar but more limited provision is found in section 13 of the Khyber Pakhtunkhwa Irrigation and Drainage Authority Act 1997, which states that "Authority, with the previous approval of the Provincial Government, shall have control over such rivers, canals, drains, streams, hill torrents, springs, reservoirs (except such reservoirs as are under the control of WAPDA) and underground water resources with-in the Province as may be specified. The conditions, under which the Province's water resources are handed over to the Authority, shall be clearly specified as to terms and conditions." In February 2020, a water bill was tabled in the parliament of Khyber Pakhtunkhwa that is similar to that presented to the Punjab government and will cover all water resources. The legal provision for managing groundwater appears to be absent in the legislation of Sindh province, though the Sindh government is actively working on a water policy.

Measuring Groundwater and Its Uses

Each province has at least a basic specific legal provision assigning a mandate to collect information about groundwater resources. Previously, under the Punjab Irrigation and Drainage Authority Act 1997, the irrigation authority was assigned the duty to monitor groundwater levels and quality and compile collected data. A nearly identical provision is found among the tasks assigned to the Sindh Irrigation and Drainage Authority in section 11(m) of the Sindh Water Management Ordinance 2002, the Khyber Pakhtunkhwa Irrigation and Drainage Authority in section 8(f)(3) of the Khyber Pakhtunkhwa Irrigation and Drainage Authority Act 1997, and the Balochistan Irrigation and Drainage Authority in section 8(f)(3) of the Balochistan Irrigation and Drainage Authority Act 1997. A similar provision is also found to be assigned to the Khyber Pakhtunkhwa Integrated Water Resources Management Board: Section 6(a) of the Khyber Pakhtunkhwa Integrated Water Resources Management Board Ordinance 2002 provides that a function of the board shall be to "acquire and maintain or cause to acquire and maintain up-to-date information and data that enables accurate resource assessment of … ground water aquifers in the Province." These province-level provisions are further complemented at the national level by the general water resources research and monitoring functions assigned to the Pakistan Council of Research in Water Resources (PCRWR) in section 4 of the Pakistan Council of Research in Water Resources Act 2007.

Sindh and Balochistan provinces go further and provide mandates to gather information on the extent of groundwater use. Thus, the Sindh Water Management Ordinance 2002 in section 33(k) provides that area water boards shall monitor groundwater withdrawals for irrigation and drainage (in addition to monitoring of groundwater quality). Section 3(6) of the Balochistan Ground Water Rights Administration Ordinance 1978 provides that the provincial water board shall arrange to determine the existing withdrawal of groundwater and maintain a register of all existing wells.

Water Resources Planning

Although legal provisions on overall water resources planning tend to be limited across Pakistan, Punjab province has recently led the way with respect to groundwater by introducing legal requirements for groundwater planning. Section 62-A of the Punjab Canal and Drainage Act (1873, specific provision introduced in 2006) provides that the provincial government shall "shall carry out the evaluation and assessment regarding the condition of aquifer, quality and availability of sub-soil water in any specified area and draw up the scheme for the proper management of the sub-soil water." Balochistan, in section 20(2) of the Balochistan Environment Protection Act 2012, provides that the regulation of sustainable abstraction of groundwater and the use of groundwater for agricultural, industrial, mining, and urban purposes should be included in water resource management plans. However, the Balochistan Act does not assign a mandate to actually undertake the development of water resources management plans. Similar provisions have not been observed in other provinces.

Allocation and Access

Sindh, Punjab, and Balochistan provinces all have at least some basic provisions governing access to groundwater and the restriction of groundwater use. Thus, for example, section 4 of the Balochistan Ground Water Rights Administration Ordinance 1978 provides for the designation of groundwater basins where permission is required before extracting groundwater. Under this section, the government furthermore has the power to stop the extraction of groundwater by unauthorized persons. Moreover, in urban areas, section 12(e) of the Balochistan Water and Sanitation Authority Act 1989 allows this authority to issue licenses for abstraction of groundwater from urban areas. In Punjab and Sindh provinces, the local government acts enacted by each province allow for the control of access to groundwater for drinking water purposes. Thus, for example, under schedule II (Optional Function Point No. 9) of the Sindh Local Government Act 2013, permission is required for the drilling of new wells and well owners must keep wells in good condition. Similar provisions are found in section 26 of the Punjab Soil Reclamation Act 1952.

Such provisions appear to be absent in the analogous legislation for Khyber Pakhtunkhwa. Across Pakistan, in the absence of subsequent specific legislation to the contrary, the historical English common law doctrine of the rule of capture applies to the extraction and use of groundwater in Pakistan (Burchi and Nanni 2003; Mechlem 2016). Under the rule of capture,[4] there are no ownership rights in groundwater until it has been extracted and landowners may sink wells and take as much groundwater as they wish (Hodgson 2006).

Protection of Groundwater Resources

Provisions for the protection of groundwater quality are limited across the provinces, but each includes at least some basics for overall water protection in their legislation. Thus, for example, section 20(3) of the Balochistan Environment Protection Act 2002 requires individuals to take measures to prevent pollution of water resources (including groundwater). Beyond this example, provincial environmental legislation generally provides for the broad power to set effluent standards for discharges to the environment.

In addition, the management of groundwater salinity takes special prominence in the legal framework of Sindh province. Under section 10(d) of the Sindh Water Management Ordinance 2002, the Sindh Irrigation and Drainage Authority is tasked with advising the government on tactical or strategic matters, such as "seawater intrusion." Section 11 further requires the authority to develop a strategy statement for the prevention of seawater intrusion and to "draft, implement and regularly update policies, studies and research programmes" on aspects such as "control of waterlogging and salinity" and "prevention of sea intrusion."

Institutions

In Pakistan's Indus basin, several institutions at the federal, provincial, and local levels are undertaking groundwater management activities. As discussed in the previous section, the mandates of these institutions can sometimes include activities to understand groundwater and its uses, planning, access, control, and protection. But the extent to which these institutions are carrying out these groundwater-related mandates and implementing additional activities varies. This next section highlights activities by the institutions most active in groundwater management. A full list of the institutions with mandates and activities related to groundwater management is provided in appendix C.

National-Level Institutions

The most active ministries in groundwater management at a national level are the Ministry of Water Resources (MoWR, through its subordinate, the Water and Power Development Authority [WAPDA]) and the Ministry of Science and Technology (MoST, through its subordinate, the Pakistan Council of Research in Water Resources [PCRWR]).

WAPDA was established by law in 1958 to undertake the development of water and energy resources in the country, and it was granted legal authority to control groundwater resources as well (see earlier discussion). The authority has a long history of developing major water infrastructure projects but less so related to groundwater, though one of its earlier functions included control of waterlogging and salinity. To address the complex problems of waterlogging, salinity, and groundwater, the International Waterlogging and Salinity Research Institute (IWASRI) was created in 1986 under WAPDA to conduct research and advise with science-based solutions. IWASRI started in 1989 with a focus on waterlogging and salinity; subsequently, it focused on drainage until 2009, during which the groundwater research was project based. In 2009, IWASRI included dedicated research on groundwater management in its program. Since then, funding constraints have limited groundwater research to small-scale, project-based activities.

The PCRWR was established in 1964 and reformed by law in 2007. Under section 4 of the Pakistan Council of Water Resources Act 2007, it has a general mandate to undertake and support research on water resources, including groundwater. PCRWR specializes in groundwater research, monitoring, and water quality management and conducts countrywide surveys of groundwater levels and quality and of drinking water quality every five years. It promotes research results through partner organizations, addressing emerging issues in irrigation, drainage, surface water and groundwater management, groundwater recharge, watershed management, rainwater harvesting, desertification control, and water quality. PCRWR has countrywide coverage through its regional offices in the provinces and its subordinate entity, the Drainage and Reclamation Institute of Pakistan (DRIP), which conducts research on drainage, salinity control and land reclamation, irrigation and drainage, and seawater intrusion. DRIP has suitably dedicated staff, equipment, and established laboratories for groundwater research.

Provincial-Level Institutions

At the provincial level, several departments undertake activities related to groundwater management, including those responsible for planning and development, irrigation, agriculture, local government, public health, environment, and municipalities. The focus of these provincial departments can broadly be divided into three groups: water management in the agricultural sector, water management for domestic uses, and environmental-quality management. Although each province's departments responsible for irrigation and agriculture have at least a limited mandate related to groundwater management (see earlier discussion), the extent of implementation and activities varies and there is little evidence of coordination among sectors.

Of the provinces, Punjab is most active in groundwater. The Punjab Irrigation Department (PID) conducts groundwater monitoring at selected locations through its Directorate of Land Reclamation (DLR), which has a dedicated laboratory for analysis of water quality parameters related to irrigation. A groundwater cell under the research wing of the irrigation department provides technical support. Punjab's Water Act requires establishing a water commission at provincial level, which will look after the cross-sectoral groundwater issues. The department is also undertaking an assessment study, which will advise on institutional structure and proportionate resource requirement for the groundwater management in the province.

For domestic groundwater supply in Punjab, the Housing, Urban Development, Local Government and Public Health Engineering Departments are active in installing tube wells and in managing them operationally. Water and sanitation agencies are mainly active in the five main cities to provide domestic water supply. The Tehsil Municipal Administrations (TMA) are active in water supply for small and medium-sized towns. Those departments and agencies develop new schemes, operate and maintain the existing tube wells and associate water supply systems, and impose tariffs and collect revenue. Regarding the management of groundwater quality in Punjab province, the Punjab Environment Protection Council has introduced environment standards for drinking water quality (Government of Punjab 2016). The DLR of the provincial irrigation department also monitors groundwater quality for irrigation.

In Sindh province, management of groundwater—mainly via the Salinity Control and Land Reclamation Project (SCARP) tube wells—is the responsibility of the Sindh Irrigation Department (SID), and the chief engineer's office in Hyderabad is active in keeping the tube wells operational. The Agriculture Engineering Directorate (of the Agriculture, Supply, and Prices Department) is also involved in converting some of the tube wells to solar energy. Mehran Engineering University, as part of an ACIAR project (*Improving Groundwater Management to Enhance Agriculture and Farming Livelihoods in Pakistan*), has established groundwater monitoring sites at Malwa Distributary in Shaheed Benazirabad District, and at Chiho Minor in Naushero Feroze District, to help farmers make informed decisions and to conduct research on groundwater behavior. In many cities and towns, groundwater is used for domestic purposes when good-quality water is available and the Public Health Department is largely active in domestic water supply, operational management of the water distribution system, and collecting revenue. The Sindh Environment Protection Agency of the Environment, Climate Change, and Coastal Development Department is mandated to take samples and conduct analyses for water quality for both surface water and groundwater. The agency can act against contraventions and can file complaints.

In Balochistan province, the Directorate of Water Resource Management within the Irrigation and Power Department is responsible for groundwater development and management. The Directorate General of Water Resource Management includes a Directorate of Groundwater Management and a Directorate of Monitoring and Planning. The Directorate of Groundwater Management is active in groundwater planning, development, and management. It had more than 500 staff members and 50 drilling rigs in 2006, when its operations were scaled back. The Public Health Engineering and Local Government and Rural Development Departments are active in the development of water supply schemes, which are then mostly handed over to communities. The Water and Sanitation Agency provides the water supply to the provincial capital, Quetta City. However, with declining water tables, many of the groundwater-based water supply schemes either switched over to a surface water source or were abandoned. The Environment Protection Agency in Balochistan was created in 1992 and presently works under the Department of Environment and Support. The agency serves as the main environment regulatory body responsible for implementation of the national and provincial laws and protecting the natural resource from degradation including groundwater.

In Khyber Pakhtunkhwa, the Hydrology Division of the Irrigation Department is mainly responsible for tube wells and large diameter wells. The Small Dams Directorate of the Irrigation Department has also conducted groundwater monitoring surveys in Bannu, Karak, and Kohat districts. For water supply, the Department of Public Health Engineering is active in rural areas, which largely use groundwater. The TMAs are responsible for water supply in small towns. The Cantonment Board is mainly responsible for specific areas designated as cantonments. The Local Area Development Authorities such as Abbotabad, Bannu, Dera Ismail Khan, Galiyat, Kaghan, Karak, Kohat, Mansehra, Mardan, Peshawar, Swabi, and Swat (all supplied by groundwater), are active in water supply in those towns and cities. The Environment Protection Agency in Khyber Pakhtunkhwa is active in preparing Environmental Quality Standards including groundwater quality.

Although the PCRWR occasionally measures the quality of drinking water as part of nationwide surveys, drinking water quality testing is not routinely conducted in any of the provinces, and it is not always evident which agencies take responsibility for conducting such testing.

Groundwater User Groups

Groundwater user groups in Pakistan are primarily informal networks of tube well owners. Information flow via these networks is socially based and unregulated. Information about better pumps may travel quickly, for example, whereas information about trends in resource conditions may not. Knowledge-based informed decision making, such as when to restrict groundwater pumping, is scarce. The management potential of these groups is limited by lack of access to technical support from responsible institutions and the inability of those institutions to disseminate groundwater information to end users. There are only a few cases in which an individual farmer or a group of farmers aim to manage their groundwater based on scientific data. One such approach is that adopted by PCRWR in collaboration with the University of Washington and National Aeronautics and Space Administration (NASA). PCRWR is providing potential evapotranspiration- and precipitation-based real-time advisory to farmers since 2016 using information communication technology (ICT) and NASA's remotely sensed data[5] to inform farmers of their net weekly irrigation requirements. The PCRWR plans to reach 100,000 farmers by 2019[6] and all farmers in the long term. In 2016, the PCRWR also initiated satellite-based monitoring of groundwater storage variations in the Indus basin.[7] This latter initiative relies on Gravity Recovery and Climate Experiment (GRACE)[8] satellite information, which, in specific regions of the world (including the Indus basin), needs to be supported and constrained by regular water level measurements (Long et al. 2015).

In Punjab, community tube wells groups were formed under the Second Scarp Transition Project (1991–97) and the Punjab Private Sector Groundwater Development Project (1997–2002) to transfer 20,000 public SCARP tube wells to these groups to control waterlogging and salinity (Kazmi and Ersten 2017) and remove the cost of operation from the government. Most of these tube wells had been installed in areas of fresh groundwater and served to supplement irrigation supplies. However, because of high operation and maintenance costs and capacity problems, this initiative was largely unsuccessful. Only 2,200 tube wells were transferred to the community tube well groups, which also faced serious

TABLE 4.2. **Community-Based Rural Water Supply Tube Wells**

Province/region	Total number of schemes	Functional schemes	Functional schemes operated by CBOs	Number of functional schemes that are operated by PHED	Share of total number of schemes that are functional (%)
Balochistan	2,353	1,746	1,005	741	74
FATA	1,507	1,228	NA	NA	81
Gilgit-Baltistan	437	437	437	Nil	100
Khyber Pakhtunkhwa[a]	4,056	3,399	1,161	2,238	84
Punjab	4,058	2,715	2,448	267	67
Sindh	1,384	666	339	327	48
Total	**21,295**	**17,652**	**12,812**	**3,612**	**83**

Source: World Bank 2013.

Note: CBOs = community-based organization; FATA = Federally Administered Tribal Areas; PHED = Public Health Engineering Department.

a. Operation and maintenance of rural schemes are no longer carried out by communities.

cost recovery problems, and their operation could not be sustained. In contrast, individual farmers installed about 1 million private tube wells throughout the country, but mostly in Punjab (Government of Pakistan 2004). These privately installed business assets tend to be well-managed and have greatly contributed to the control of waterlogging in areas of fresh groundwater.

Although irrigation groundwater monitoring systems have so far been disappointing, Pakistan's municipalities and each provincial Public Health Engineering Department (PHED) have successfully developed many community-based tube wells for domestic water supply. A World Bank study (2013) showed that there were 21,295 rural water supply schemes in Pakistan, out of which 17,652 (83 percent) were functional (table 4.2).

Of the functional schemes, 12,812 were operated by community-based organizations (CBOs) and the rest by the PHED (World Bank 2013). Accepting CBOs as legal entities with the ability to raise funds and extend services, combined with technical and financial support from the PHED, were found to be key elements. Considerable background work was done on social mobilization and CBOs' institutional structures prior to their formation. Despite this, groundwater regulation remains almost nonexistent, and pumping tends to be limited by local aquifer conditions only. As part of an Asian Development Bank project in the Punjab, CBOs were formed in villages participating in a Community Water Supply and Sanitation Sector Project that involved 500 communities. The project completed 778 water supply, drainage, and sanitation subprojects in 30 districts, and CBOs in the project villages participated in their planning and implementation and assumed responsibility for tube well operation and maintenance. The CBOs were trained in operation and maintenance, tariff setting, revenue collection, bookkeeping, and basic accounting. However, meeting operation and maintenance costs remained a challenge.

Although the community groups described earlier have had mixed success to date, these networks represent important social structures with the potential to be coordinated and revitalized. Groundwater management relies essentially on decentralized private tube well owners knowing the collective impact of their pumping activities, understanding what regional groundwater management requires of them, and having the incentives to make interventions. In the absence of the necessary information and clear guidance from government, the state of groundwater deterioration is not surprising.

Monitoring Groundwater Resources in the Indus Basin

At the federal level, WAPDA established the SCARP Monitoring Organization (SMO) in the 1960s to undertake groundwater monitoring in the Indus basin, focusing mostly on Punjab and Sindh and based on previous technical studies (Hunting Technical Services 1965, 1966). The SMO mandate included the performance of SCARP tube wells, water level observations pre- and post-monsoon, and the chemical quality (salinity, sodium adsorption ratio [SAR], and residual sodium carbonate index [RSC]) of groundwater from SCARP tube wells. This work generated valuable data on water levels and basic water quality. However, most of it is handwritten in field books in SMO offices and is not available in digital format. IWASRI and SMO Sindh have indicated that monitoring of SCARP tube wells stopped in 2015 as a result of lack of funding and the shift in responsibility from the federal to the provincial level. Many of the SCARP tube wells have also been abandoned because of their disintegration from lack of maintenance and reaching the end of asset life.

Responsibility for monitoring those SMO wells that still exist, and rehabilitating abandoned wells, currently lacks an institutional home and appears to have reached an interjurisdictional stalemate. The necessary roles and budget, together with a strategic monitoring plan and protocols for monitoring and sampling, need to be agreed between federal and provincial governments.

More recently, the PCRWR has monitored groundwater levels and water quality in the Indus basin on a project basis. The PCRWR also conducts extensive monitoring of potable water quality. These data are, however, difficult to access and use, and coordinates are often not available. The sharing of data between federal and provincial agencies is also often complicated as a result of access restrictions, different formats, and poor availability of metadata.

At the provincial level, PID relies on a network of DLR bores to monitor groundwater. Punjab has a monitoring strategy in place, particularly in the eastern doabs, though it is reliant on manual methods. Water levels and salinity are measured pre-Kharif (June) and post-Kharif (October)—typically including depth to water, conductivity, SAR, and RSC—and are focused mostly in the eastern doabs of Punjab. Challenges include data reliability and nonfunctioning bores. Monitoring borehole locations are also often not ideal. PID is also trialing digital loggers in selected bores. The Australian Center for International Agriculture Research (ACIAR) project on improving groundwater management to enhance agriculture and farming livelihoods[9] has established monitoring sites in Okara and Sahiwal, instrumented with water level and conductivity loggers (ACIAR 2016). See box 5.1.

TABLE 4.3. Summary of Availability of Groundwater Information and Data

Department	Data	Comments
IWASRI/WAPDA	Borelogss Groundwater levels, salinity, and limited water quality parameters from SMO wells in Punjab and Sindh (1980–2000); more patchy data from 2000–15; data from 2010–15 in digital form	Time series (pre- and post-monsoon) depth to water data collected from SMO wells from 1980–2000. Patchy monitoring has continued up to 2015. • Access to data may be difficult. • Published maps may be available. • Significant data checking will be required if access is available.
PCRWR	Borelogs Monitoring of groundwater levels and salinity in Punjab and Sindh (recent information only) Water quality data in urban centers are also collected (water quality is evaluated on a five-year basis; reports are published and should have credibility)	Monitoring was undertaken at spatial scale of 25 x 25 km in Pakistan's Indus basin. The information can offer a snapshot of water levels. • Time series data may not be available. • Use of this data requires scrutiny; coordinates may not be correct in some cases.
PID	About 3,000 DLR bores drilled, of which about half are nonfunctioning Water levels, conductivity, and analysis of SAR and RSC in the doabs	Data are archived with PID. Use of this data requires close scrutiny because of errors in data; coordinates may not be correct in some cases. Surface water data collection and archiving is much more systematic as PMIU unit is responsible.
SID	No systematic monitoring data available on groundwater levels and salinity	Some data are available in consultant reports. Data collected on specific projects are held privately with individual researchers.
IUCN, WWF, consultant reports on projects funded by donors and development banks and research projects	Project-based data may be available Good data in delta areas on ecosystems Groundwater and salinity data limited, if any	Access to data held by consultants is generally not available. However, there are a number of good reports that have data that can be used (for example, ACE, EGC, and SMEC 2011; FoDP, World Bank, and IUCN reports). The LIP reports in Sindh from the mid-1960s are a good source of data on groundwater systems. In Punjab, the Lower Bari Doab modeling study funded by ADB and the Rechna Doab study under the ACIAR project are also sources of data.
WASA, PHED	No monitoring of groundwater extraction May collect some water quality data	Extracts groundwater for urban water supply. Some data may be available in reports and in field books.
NGOs and private sector initiatives	Some data are collected, which are project focused, localized, and short-term initiatives	Lacks coordinates and water quality analysis. Reports show that they have supported community-based initiatives.

Note: ACE = Associated Consulting Engineering; ACIAR = Australian Center for International Agriculture Research; ADB = Asian Development Bank; EGC = Engineering General Consultants; DLR = Directorate of Land Reclamation; FoDP = Friends of Democratic Pakistan; IUCN = International Union for Conservation of Nature; IWASRI = International Water Logging and Salinity Research Institute; km = kilometer; LIP = Lower Indus Project; NGOs = nongovernmental organizations; PCRWR = Pakistan Council of Research in Water Resources; PHED = Public Health Engineering Department; PID = Punjab Irrigation Department; PMIU = Project Management and Implementation Unit; RSC = residual sodium carbonate index; SAR = sodium resorption ratio; SCARP = Salinity Control and Land Reclamation Project; SID = Sindh Irrigation Department; SMEC = consultant name; SMO = SCARP Monitoring Organization; WAPDA = Water and Power Development Authority; WASA = Water and Sanitation Agency; WWF = World Wide Fund for Nature.

A stated policy objective of the National Water Policy 2018, signed by representatives from all governments in Pakistan, is on "upgrading water sector information systems for improved asset management and to derive evidence and data driven decision making."

At present groundwater planning is constrained by the lack of adequate long-term data on groundwater systems in the Indus basin in Pakistan. Without the required investment, groundwater use will continue in an unregulated manner until the government is forced to react to a crisis. The planning and institutional arrangements for regular monitoring and maintenance of assets is equally important.

Groundwater Data Sets

Disparate groundwater data sets are scattered among several federal and provincial institutions (see table 4.3), and much of the historic data remain in paper format. These paper data sets are perceived as being reliable, but this can be assessed only once they are digitized. Recent data sets (since 2010) are online; however, they lack reliability.

The data accessed for this report indicate that there are problems with data collection methods, which resulted in a small subset of data being considered for analysis. It is clear that a lack of protocol leads to inconsistencies in data collection and recording. Many of the measurements are clearly erroneous and point to the possibility that, in some cases, data have been estimated rather than measured.

Implications of Inadequate Data on Groundwater Sustainability

The rapid growth in groundwater irrigation has played a major role in increasing cropping intensities in the Indus basin and improving food security for Pakistan. Growing disbenefits, such as salinization and falling water tables, increasingly demand better groundwater management. Because much of the groundwater recharge in the Indus basin is a result of canal seepage and irrigation return flows, integrated approach to the management of surface water and groundwater is required to achieve sustainable outcomes by improved conjunctive water management (Kamal 2009).

A number of groundwater models have been constructed over the years (see appendix A), usually at sub basin or doab scale. These have used several different modeling codes and protocols and have generally been aimed at investigating a particular problem, such as water-level changes or salinity buildup. Such models are potentially very useful management tools, particularly as they are updated and upgraded as new data become available. Model utility and accuracy depend heavily on the availability of good-quality, accurate groundwater data, particularly time-series data.

Data quality and access is a key constraint in Pakistan, and data sources are highly fragmented, with ownership residing across federal and provincial government agencies. Although this problem is common in other parts of the world, including the United States (Josset et al. 2019), decisions based on models with a partial understanding of the system likely result in low predictive value. Most of the models developed to date are based on short-term data sets of less than five to seven years. None of the models have gone through a rigorous review and verification process, largely because of the lack of systematic spatial and temporal data sets.

Notes

1. A karez is a traditional method of extracting groundwater. It is a gently sloping tunnel, constructed into a water-bearing formation at the base of a mountain, that conveys groundwater under gravity to the land surface downgradient. Adapted from: https://link.springer.com/chapter/10.1007/978-3-030-00728-7_22
2. (Prior to Eighteenth Amend.) Item 24, fourth sched., Const. of Pakistan (1973).
3. Art. 70(4), 154(1) and fourth sched., part II, item 3, Const. of Pakistan (1973).
4. Stated in the English court decision Ballard v. Tomlinson, 29 Ch. D 115 (1885) (see Hodgson 2006 for further discussion).
5. For more information, see the PCRWR website at http://www.pcrwr.gov.pk/advisory.php.
6. DG Dr Muhammad Ashraf (now Chairman), PCRWR. By telephone with author. March 2019.
7. For more information, see the PCRWR website at http://www.pcrwr.gov.pk/hq.php?view_st
8. The GRACE mission consists of twin satellites that measure the Earth's gravity field to determine changes in the mass of water bodies, ice sheets, and so on over time.
9. https://aciar.gov.au/project/lwr-2015-036

References

ACIAR (Australian Center for International Agricultural Research). 2016. "Improving Ground Water Management to Enhance Agriculture and Farming Livelihoods in Pakistan." FAC Sheet, ACIAR, Canberra. Accessed November 2019. https://cdn.csu.edu.au/_data/assets/pdf_file/0011/2703845/Ground-Water_FAC_sheet.pdf.

Burchi, Stefano, and Marcella Nanni. 2003. "How Groundwater Ownership and Rights Influence Groundwater Intensive Use Management." In *Intensive Use of Groundwater, Challenges and Opportunities,* edited by Ramón Llamas and Emilio Custodio. Lisse, The Netherlands: A.A. Balkema. 227-240.

Government of Pakistan. 2004. *Pakistan Agricultural Machinery Census 2004*. Statistics Division, Agricultural Census Organisation, Lahore, Pakistan.

Government of Punjab. 2016. "Regarding the Punjab Environmental Quality Standards for Drinking Water." *The Punjab Gazette,* August 15. Lahore, Pakistan.

Hodgson, Stephen. 2006. "Modern Water Rights: Theory and Practice." FAO Legislative Study No. 92, Food and Agriculture Organization, Rome.

Hunting Technical Services Ltd and Sir Mott MacDonald and Partners. 1965. Lower Indus Report, Physical Resources-Groundwater, Volume 6, Supplement 6.1.3, 4 and 5. West Pakistan Water and Power Development Authority.

——. 1966. Lower Indus Report, Part One, Present Situation. West Pakistan Water and Power Development Authority.

Josset, L., M. Allaire, C. Hayek, J. Rising, C. Thomas, and U. Lall. 2019. "The U.S. Water Data Gap—A Survey of State-Level Water Data Platforms to Inform the Development of a National Water Portal." *Earth's Future* 7: 433-49. https://doi.org/10.1029/2018EF001063.

Kamal, S. 2009. "Pakistan's Water Challenges: Entitlement, Access, Efficiency, and Equity." In *Running on Empty*, edited by M. Kugelman and R. M. Hathaway, 28-34. Washington, DC: Woodrow Wilson International Center for Scholars.

Kazmi, S. I. H., and M. Erstem. 2017. *Changes in Tube Wells Count in Two Decades in Area under Conjunctive Irrigation in Pakistan*. Delft, The Netherlands: Delft University of Technology. https://www.academia.edu/1414064/CHANGES_IN_TUBE_WELLS_COUNT_IN_TWO_DECADES_IN_AREA_UNDER_CONJUNCTIVE_IRRIGATION_IN_PAKISTAN.

Long, D., L. Longuevergne, and B. R. Scanlon. 2015. "Global Analysis of Approaches for Deriving Total Water Storage Changes from GRACE Satellites." *Water Resources Research* 51: 2574-94. doi:10.1002/2014WR016853.

Mechlem, Kerstin. 2016. "Groundwater Governance: The Role of Legal Frameworks at the Local and National Level - Established Practice and Emerging Trends." *Water* 8: 347.

World Bank. 2013. *Pakistan Water and Sanitation Sector, Volume II: Rural Water Supply and Sanitation*. Washington, DC: World Bank. https://hudphed.punjab.gov.pk/system/files/8%28b%29-Pakistan%20Rural-Vol%20II_v3%2012-6-13%20print.pdf

Chapter 5
Management Solutions

Key Points

- Policy documents at national and provincial levels are increasingly emphasizing a focus on groundwater management.
- Groundwater challenges in the Indus basin are well understood, in common with other parts of the region.
- Management decisions rely on adequate planning, which in turn is based on reliable and representative data.
- Many available techniques exist that are adaptable to support satisfactory groundwater management outcomes in the Indus basin, and examples are provided at the provincial, national, regional, and international scale that show promise.

Introduction

The principles of sustainable groundwater management are understood in Pakistan, as identified in outputs from government, academia, and policy institutions for the past several decades. However, as indicated in previous chapters, this understanding has not yet led to the implementation of legislation or policies resulting in actions to manage the resource adequately. Pakistan is not the first country to experience the challenge of starting the process of groundwater regulation long after problems have appeared in its management. Examples of tackling this issue can be found in many parts of the world, and similar situations are reflected in India and its state governments as well as further afield, such as in the United States and Australia.

Institutional Reform

Pakistan's National Water Policy 2018 (Government of Pakistan 2018) recognizes the ongoing challenges for groundwater and provides clear intentions for the road ahead on groundwater governance and management in Pakistan.

Necessary reforms, as foreshadowed in the policy, require defined federal and provincial roles (both are important for this international and interprovincial transboundary aquifer) and budgetary provision to enable those roles to be fulfilled. This entails both the drafting of legislation that defines the framework under which the resource will be regulated and the remodeling of institutions to support the enactment of that legislation and to confer institutional responsibility for managing groundwater.

As a regional example, the Central Ground Water Board (CGWB)[1] is the apex organization of India's Ministry of Water Resources (MoWR) dealing with groundwater matters. Established in 1970, it has the mandate to provide oversight and support for technologies, policies, and the sustainable management of groundwater resources in the country. It works with state water departments, many of which include a prominent groundwater wing. To support the states in enacting groundwater legislation, a "Model Bill to Regulate and Control Development of Ground Water" (Government of India 2005) was created by the MoWR to assist state governments.

California has experienced extensive challenges, including widespread depletion, associated with an inadequate legal framework for groundwater and a fragmented approach to its management. Since 2014, it has embarked on the difficult and lengthy process of reform by the sequential introduction of legislation, regulations, and a compliance regime.[2] Some provinces in Pakistan have commenced the process of reform by introducing legislation that confers responsibility for water management, including groundwater (for example, the Punjab Water Act 2019 and a similar bill placed before the Khyber Pakhtunkhwa parliament in February 2020). The responsibilities of lead agencies are yet to be allocated, ensuring that there is a coordinating role to guarantee collaboration from all sectors and all tiers of government (including community participation).

Co-management through Community Participation and Stakeholder Involvement

Stakeholder engagement and community participation have long been recognized as central to successful groundwater management strategies and must be considered an essential component of institutional reform. Many of the important initiatives that are part of current water management approaches, such as basin planning and conjunctive water management, rely on the effective engagement—and direct involvement—of groundwater users, as outlined in the report on integrated basin planning (World Bank 2006). This report highlights good practice, such as those used by the Mekong River Commission, and discusses examples of less helpful approaches. Although particularly important in situations in which institutions are weak, community participation can also play an important role in more regulated situations. Initiatives identified in the National Water Policy 2018 promise a larger role for local decision makers and a greater voice for local groundwater users.

Several examples of community participation in groundwater management exist in India, such as the recently commenced Indian National Groundwater Management Improvement Program (Atal Bhujal Yojana[3]) that puts community participation at the center of water budgeting and water security plans at the block level. Many nongovernmental organizations (NGOs) facilitate various models of this—for example, Managing Aquifer Recharge and Sustaining Groundwater Use through Village-Level Intervention (MARVI)[4] focuses on developing an effective participatory groundwater monitoring program at village level.

A discussion of co-management of groundwater through local action by farmers in an irrigation area in Australia can be found in Shalsi et al. (2019). Although established in a regulated system that doesn't yet exist in Pakistan, the paper demonstrates how user groups can lead the government on essential data collection, policy changes, and planning initiatives that result in long-term sustainable groundwater use.

A local example that can be built on is provided by a project in Pakistan, supported by the Australian Center for International Agricultural Research (2016), that treats farmers as researchers so that they are integral to data collection, data analysis, trend prediction, and decision making (see box 5.1).

BOX 5.1. Improving Groundwater Management to Enhance Agriculture and Farming Livelihoods in Pakistan

A four-year project (started in 2016) funded by the Australian Centre for International Agricultural Research (ACIAR), Charles Sturt University (CSU) and the Government of Pakistan to build capacity to manage groundwater resources at case study sites in Balochistan, Punjab, and Sindh for improved social, economic and environmental benefits.

Three project objectives:

1. Improve Groundwater management by farmers and/or farming organisations.

2. Partner government agencies have improved groundwater planning, monitoring and management strategies, and guidelines for legislative change.

3. Responsible provincial government agencies, non-governmental organisations and farmers' organisations have developed partnerships for discussion of groundwater issues/solutions

Monitoring: Establishing groundwater monitoring sites in case study areas has enabled good personal relationships to develop between groundwater researchers, managers from the project team and local farmers. Some monitoring sites were established on farms, and farmers have assumed responsibility for the security of these sites and their equipment. These initial interactions indicate the benefit of nurturing a sense of ownership of case study design and outcomes by local farming families.

PHOTO B5.1.1 Measuring Depth to Water Table

Source: JF Punthakey.

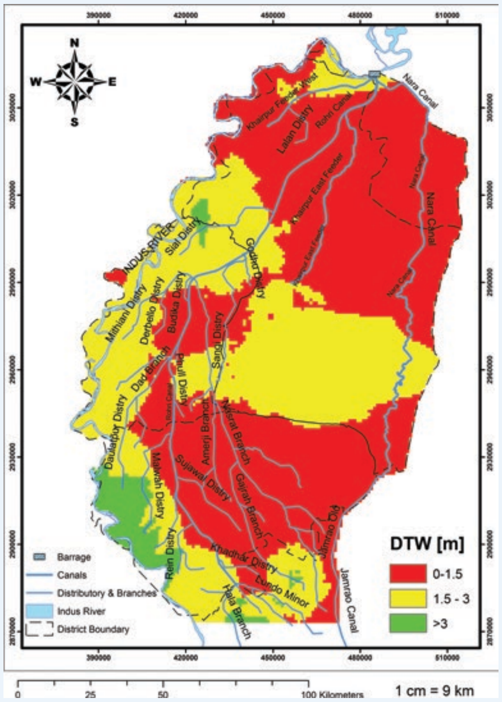
Groundwater models to improve spatial and temporal understanding of the groundwater system, and to explore the impact of pumping, irrigation and climatic conditions on water level trends (map B5.1.1).

box continues on the next page

BOX 5.1. continued

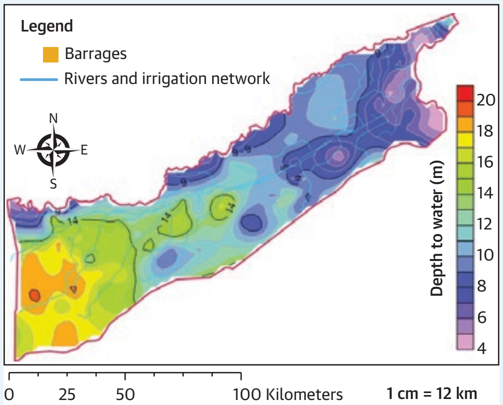
Groundwater levels are declining in Sahiwal and Khanewal districts of the Lower Bari Doab Canal command area, at an average rate of 0.3-0.4m per year, while they show an upward trend in Okara district (map B5.1.2).

MAP B5.1.1. 2014 Postmonsoon Depth to Water Table



Source: Jay Punthakey.

MAP B5.1.2. Depth to Groundwater, Jun 2010



Source: Jay Punthakey.
Note: GW = groundwater.

Economic modeling: will help inform farming communities of the options available for suitable crops, the benefits of adopting climate smart agricultural practices and understanding the consequences of change (e.g. changing crop types or water use). Improving water productivity of irrigated agriculture supports a sustainable future for agricultural communities that help them plan for better futures

Capacity building: The groundwater models, developed together with the Provincial Irrigation Departments in each of Sindh, Punjab and Balochistan are the central focus for building capacity in-country to improve monitoring, modelling and management of groundwater.

The models will allow an in-depth analysis of the water balance to estimate sustainable yield of the aquifer. Moreover, they will allow scenario analysis to improve understanding of the impacts of growth in groundwater usage and an uncertain climate future. Model outputs support discussion on what is happening to our groundwater, the trends over time, the different conditions in different places, and to explore how much we can safely use.

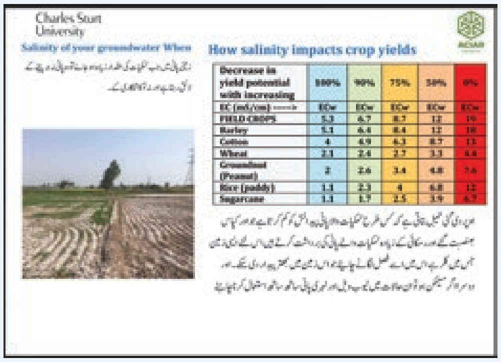
box continues on the next page

BOX 5.1. continued

Groundwater information: The objective to build essential skills, knowledge and confidence within farming communities, government agencies and NGOs is supported by providing information, tools and processes to improve groundwater planning and management to enhance agricultural sustainability in Pakistan. Information has been compiled in formats friendly to extension agents and farmers, including: a Groundwater booklet; an On Farm Water Management booklet; and Farmer Cards. The Farmer Cards present key groundwater related issues simply and cover one topic per card. These resources have been translated into Urdu and Sindhi to benefit groundwater users and farming communities.

Groundwater - Its importance in Pakistan

Role of groundwater



Charles Sturt University

Salinity of your groundwater When

How salinity impacts crop yields

Decrease in yield potential with increasing	100%	90%	75%	50%	0%
EC (mS/cm) ------>	ECw	ECw	ECw	ECw	ECw
FIELD CROPS	5.3	6.7	8.7	12	19
Barley	5.1	6.4	8.4	12	18
Cotton	4	4.9	6.3	8.7	13
Wheat	2.1	2.4	2.7	3.3	4.4
Groundnut (Peanut)	2	2.6	3.4	4.8	7.6
Rice (paddy)	1.1	2.3	4	6.8	12
Sugarcane	1.1	1.7	2.5	3.9	6.7

Basin Planning

Basin planning comprises the activities associated with making land and water management decisions that address the economic, environmental, and society tradeoffs in a fair manner (World Bank 2006). The need for better data on groundwater in the Indus basin has already been described and is both required for and supported by basin planning. The cross-cutting nature of water data (that is, the extent to which it affects numerous sectors) has been described by the World Bank and United Nations (HLPW 2018), and the need for evidence-based decision making has been emphasized. Although an understanding of basin water resources is important nationally, the building blocks of a basin plan are the local plans, and groundwater management is effectively achieved on a local scale, such as a canal command area.

Delineation of Water Management Areas

The delineation of groundwater management areas is essential to support planning at any scale and a necessary step toward improved groundwater management. The lateral boundaries of these areas consider natural, political, and administrative boundaries. For groundwater, though respecting natural flow and quality characteristics, these boundaries should be determined in consultation with stakeholders. There have already been initiatives to define groundwater management areas in Pakistan—for example, the Punjab Private Sector Groundwater Development Project (1997-2002), which sought to establish groundwater management areas and a monitoring database and develop a regulatory framework for groundwater management (PPSGDP 2000). Lessons learned in this project may apply across the Indus basin. The CGWB of India's Manual on Aquifer Mapping may also be a useful resource.[5]

Characterizing the Resource: Static Data

The lateral and vertical dimensions and characteristics of the resource need to be identified within the management area, and the connections to adjacent management areas and other water bodies established. The Indus basin exhibits a heterogeneous distribution of sediments, typical of an active fluvial environment. Because these influence groundwater behavior (refer to chapter 3), an improved understanding of aquifer geometry in the basin (including information from deeper drilling logs) would support the understanding of how to manage the resource at the local scale.

Such an understanding of the distribution and thickness of strata, their hydraulic properties, and the natural distribution of salinity would support the planning of groundwater use and management actions (such as managed aquifer recharge [MAR]). In India, aquifer mapping, including the use of novel airborne electromagnetic (AEM) techniques has been incorporated into federal policy programs such as the National Project on Aquifer Management (NAQUIM) of the CGWB.[6]

This understanding would be enabled by deeper boreholes and associated drilling logs, accurate recording of borehole construction, and more accurate recording of salinity information with depth, critical for managing the risk of saltwater upconing.

Characterizing the Resource: Dynamic Behavior and Water Budgets

An understanding of how water levels and salinity respond to natural phenomena (rainfall, evaporation, seasonal changes) and anthropogenic pressures (pumping, irrigation, agrichemical use) supports long-term predictions and planning and allows modeling of unusual events (climate- and disaster-related). Therefore, the frequency of measurements needs to be more often than twice a year and labeled with much greater temporal precision than the current custom of pre- and post-monsoon.

Field data collection instruments include handheld water-level dippers and electrical conductivity (EC) meters, as well as more sophisticated automatic water-level recording devices and downhole logging tools (such as for measuring salinity). It is important to have confidence in such data because decisions taken have far-reaching financial and human consequences, so even the most basic of data collection activities ordinarily rely on protocols that cover field instrument calibration and use; data recording and storage; and groundwater sampling and laboratory analysis. These are in addition to protocols for quality assurance and control.

Digital technology solutions, such as automated data loggers (including those linked by telemetry), are a valuable investment, complementary to manually measured data and remotely sensed data, such as AEM data acquisition (mentioned earlier) or from the Gravity Recovery and Climate Experiment (GRACE) satellites, building on the existing Pakistan Council of Research in Water Resources (PCRWR) project.

The linking of automated data collection at local scales with wide area remote sensing has the potential to amplify the impact of both. Crowdsourcing of water data may also present significant opportunities for local data collection.[7]

Irrespective of how it is collected, time series data are an essential component of managing water resources anywhere in the world (Josset et al. 2019; see discussion of modeling in appendix A) and form the very basis of developing the water budget.

The calculation of a water budget is the basic building block of water resource planning and entails an understanding of inflows and outflows to a system over a period of time. The Indian government's Groundwater Estimation Committee, active since 1984, has developed a methodology for determining groundwater budgets that can be applied at the village or district level using data sets derived from basic local measurements (Ground Water Resource Estimation Committee 2017). Using this, and antecedent methods, the government of India has been able to track and map groundwater behavior across the nation for the past two decades. Although the methodology has recognized flaws (Ravenscroft, Kumar, and Purohit 2019), it provides a solid starting framework on which a more locally specific technique can be built.

In addition to the collection of groundwater measurements are the information systems that allow data archiving, access, and transparency. How and where data are stored and retrieved, the accessibility and flexibility of these systems, and the institutional systems that ensure continuity are all vital components of an effective groundwater monitoring system (see, for example, India's Water Resource Information System [WRIS],[8] developed under the National Hydrology Project[9] and the Andhra Pradesh Water Resources Information and Management System[10]).

The interdependency of groundwater and surface water in Pakistan's Indus basin suggests that the water resource (river, canal, and groundwater) should ideally be monitored and managed as a single entity, with close collaboration and common data standards. The value of properly curated data in a robust data management system has several components, including preserving the record; enabling planning and prediction (including modeling); supporting allocation decisions; evaluating the impact of future events and scenarios; and supporting research and innovation. The monitoring showcased in the ACIAR project (see box 5.1) provides a current example of this approach.

The mathematical modeling of groundwater flow and the transport of contaminants is a powerful tool to manage groundwater and predict future outcomes. It is most effective when conducted with robust and long-term data sets (see appendix A). Modeling is an activity that needs to be contested, contestable, and—for situations such as the Indus—developed as part of an integrated approach, with cross-sectoral inputs, and on sound participatory management principles.[11]

Conjunctive Management of Surface Water and Groundwater

As identified in chapter 3, the intimate connection between surface water and groundwater in the Indus basin has led to waterlogging and land salinization in some areas. In other areas, it has led to the overestimation of available resources because of double accounting (see Evans, Evans, and Holland 2013) and the resultant depletion and salinization of groundwater resources. The conditions in the Indus basin represent an excellent example of where equitable distribution of water resources and their sustainable use could be achieved under a conjunctive management framework.

Conjunctive management in irrigation areas refers to a strategic approach in which surface water and groundwater use are jointly managed at the canal command level and optimized both for the benefit of users and water resources. At the resource level, groundwater pumping for irrigation used in conjunction with surface water provides benefits, including a better distributed water supply and drought mitigation as well as control of shallow water tables and consequent soil salinity (Petheram, Bristow, and Nelson 2008).

The technique relies on a sound working knowledge of the entire water budget: both the surface water (that is, the canal system) and the groundwater (that is, the spatial distribution and seasonal variation of groundwater depth and salinity) combined with an understanding of specific water demands throughout the year, as well as an ability to control them. Other inputs (such as precipitation) and outputs (such as drainage and evapotranspiration) are also essential to understanding the water budget and to applying this management technique, particularly when saline soil or groundwater is a component of the waterlogged condition.

Management options include encouraging farmers at the head of the canal to use groundwater to meet crop water requirements, improving canal water distribution at the canal command level to ensure equity for tail-end farmers, managing groundwater and surface water deliveries in areas of shallow and/or saline groundwater, and valuing improvements to saline groundwater by canal seepage.

There is considerable potential for this technique in the Indus basin. In Sindh, for example, the persistent waterlogging associated with the command areas of nonperennial canals suggests that the use of groundwater could be sustainably increased in some areas. A good illustration of this dynamic is presented by Lashari et al. (2015) who cite the example of Rice Canal near Larkana where the water table fluctuates between 1 and 3 meters between Rabi and Kharif seasons. Water tables rise during Kharif as canal duties are very high in nonperennial canals, and during Rabi, when canal flows cease, the water tables drop. Lashari et al. (2015) propose that by restricting surface water, farmers would need to use some groundwater, which would provide benefits by controlling waterlogging. Steenbergen, Basharat, and Lashari (2015) found that only a fraction of the available annual renewable groundwater of 22 billion to 27 billion cubic meters is used by crops, contributing to waterlogging and soil salinity. Rebalancing surface water and groundwater use in Sindh by conjunctive management promises to release surface water for other uses, lower the water table, reduce salinity, increase agricultural production, and improve health. It is a viable solution to low productivity and land degradation in Sindh (Lashari et al. 2015).

Conjunctive management is mentioned in the policy documents of several countries in the region (such as Bangladesh's National Water Policy 1999 and the Irrigation Policy of Nepal). ACE et al. (2011) refer to the lack of institutional coordination and collaboration in Pakistan required for the effective deployment of conjunctive management and indicate the two fundamental requirements of government regulatory capacity: regulating the delivery of service and regulating the use of water resources. The Burdekin Delta in Queensland, Australia, provides an international example of a fully operational managed conjunctive use system in a sugar cane growing area.[12] MAR (see the next section) is another tool in the conjunctive management story in which excess surface water can be diverted to areas of depleted groundwater for enhanced recharge.

Managing Waterlogging and Salinity

The widespread incidence of waterlogging and associated salinity in Sindh means these two related problems require special management attention in that province. Addressing the waterlogging issue has been an essential goal of provincial drainage plans since the 1960s, but the problem remains stubborn. The Left Bank Outfall Drain (LBOD) project was constructed in the 1980s and 1990s and planned to drain Mirpur Khas, Nawabshah, and Sanghar districts, an area of 1.3 million acres on the left bank of the Indus in Sindh (World Bank 2005). The project planned to use a combination of surface and subsurface drainage and on-farm water management to improve productive agriculture by lowering the shallow saline water table. The design of the scheme involved the use of deep tube wells, scavenger wells, buried interceptor drains, and tile drains, which discharge drainage effluent to surface drains and eventually discharge to the sea via a spinal drain and tidal link canal. Various numerical groundwater models exist for the LBOD area, as described in appendix A.

The operation and management of any scheme of this magnitude requires close monitoring and assessment, which was lacking because of resource constraints and inadequate institutional arrangements (Punthakey et al. 1997). The performance of the major drainage components of the scheme encountered many problems, particularly following periods of exceptionally high rainfall, although for groundwater, Lashari and Kori (2011) reported the effectiveness of the scavenger wells that extracted shallow fresh groundwater from the surface for irrigation while deeper saline groundwater was extracted, for disposal, from the same tube well but using a separate pump. However, these are complex to operate, and there is anecdotal evidence that they no longer function as designed. This may be a result of poor installation, the absence of required technical understanding of how to operate them, lack of motivation to operate them correctly, or the structures having reached the end of their asset life.

Although conjunctive management, as indicated earlier, is also one of the essential tools to combat waterlogging in some areas, some parts of the canal command areas have a combination of waterlogging and saline groundwater that inhibits the use of the land and water. In this context, Habib (2010) identifies the essential combination of effective drainage and saline agriculture to achieving a secure future for agriculture in Sindh, and others (Qureshi 2011; Qureshi and Sarwar 2009) detail alternatives for saline agriculture that are adapted to different types of groundwater salinity.

In many parts of Sindh, groundwater exists in the form of thin freshwater lenses that overlie deeper saline groundwater. These areas are tapped by shallow tube wells and hand pumps, which provide important domestic water supplies. If pumps are installed at too great a depth or extract at too high a rate, there is a risk that the deeper saline groundwater will be drawn up into the freshwater lens by upconing (see box 5.2). The safest way to access this fresh groundwater without causing salinization from the deeper groundwater is by skimming wells, as shown in box 5.2, and research conducted in Pakistan shows the promise of this technique (Ashraf et al. 2012, Sheikh and Batti 2007; Saeed and Ashraf 2005).

Many such wells were installed as part of the LBOD project, though studies indicate that the performance of these was poor when installed without taking account of site-specific knowledge, such as aquifer lithology and groundwater salinity profile, but instead to suit the tube well options provided by local drillers (Saeed and Ashraf 2005). A survey of these wells conducted over three years from 2009-12 indicated that 31 percent of them were either abandoned or had their operations limited within the first three months after installation (Chandio and Lee 2012). As a result of a lack of proper well design, either the pumping capacity reduced or water quality deteriorated within a few months of installation (see also the modeling assessment in appendix A), which is not to cast doubts on their utility but to emphasize the requirement for these to be expertly designed, installed, and operated. When these shallow lenses provide domestic water supplies, and are supported by seepage from canals (Ensink et al. 2002; Jensen et al. 1998), any decision to line such canals must be taken with an understanding of the impact it will have on the dimensions of the freshwater lens and the requirements of dependent users.

Areas with EC values exceeding 3,000 microsiemens per centimeter need close monitoring and assessment. Use of groundwater in these areas without appropriate blending with fresher groundwater or surface water will increase salinity concentrations in the root zone. Monitoring of depth to water, EC, and vertical salinity profiles via nested piezometers throughout Sindh would equip decision makers with necessary information and, in turn, protect the resource and enhance agricultural productivity. This is because the viability of agriculture with higher cropping intensities depends on the ability to exploit the freshwater lens and minimize upconing of saline groundwater from the deeper parts of the aquifer (see box 5.1) where salinity concentrations can exceed that of seawater. Once a fresh groundwater body becomes salinized, it can take generations for the problem to be reversed, even with good management.

Seawater intrusion (see box 3.4) is another distinct technical challenge. MWH, ACE and NESPAK (2005) conducted a detailed groundwater modeling assessment of seawater intrusion to the Sindh aquifer below Kotri Barrage that provided a detailed analysis of the freshwater budget and the steps required to balance water budgets to avoid saline intrusion. The relationships of the water bodies (river, canals, groundwater, ocean) are complex and change with location, and the solutions are location specific. More details on this work are provided in appendix A, and examples of regional solutions are discussed in the following section.

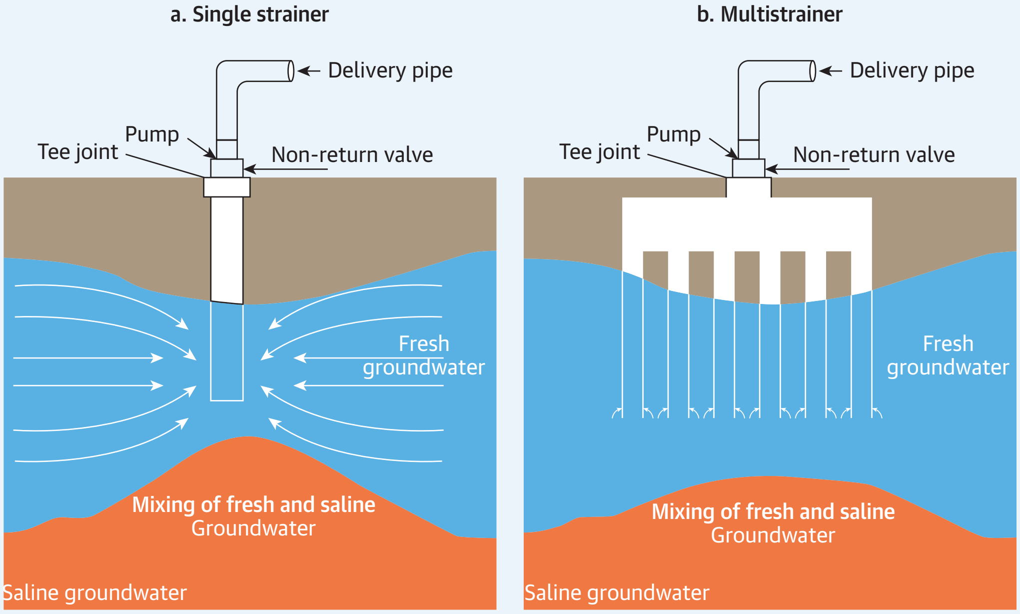
Demand Management and MAR

Demand management is essential in the water resource management toolbox and will become more important as the population grows and demand naturally increases, particularly if climate change also affects water availability. Facets of demand management include crop choice, irrigation changes,

BOX 5.2. Skimming Wells and Salinity

Skimming wells are used to extract freshwater from a relatively thin freshwater lens that overlies saline groundwater. They can be a single strainer well or multistrainer wells, are typically low discharge (less than 28 liters per second), consist of a cluster of wells drawing groundwater from relatively shallow depth, and are generally designed for irrigation or drinking water supply. These wells extract water from relatively shallow depths, and the low discharge rates are designed to reduce the risk of saltwater upconing.

FIGURE B5.2.1. Skimming Well Design: a) Single Strainer; b) Multistrainer



Source: **Authors (after Ashraf et al 2012).**

Unregulated groundwater pumping often results in upconing, which results in increased salinity of groundwater that is being pumped. During drilling, the electrical conductivity (EC) of groundwater samples are taken. When EC reaches 3,000 microsiemens per centimeter, drilling is stopped, and this depth is taken as the interface between fresh and brackish water. Skimming wells are usually installed at 40 percent penetration ratio. So if the depth to water is 5 meters, the fresh brackish zone is at 30 meters and the well is drilled to 15 meters. Skimming wells should not be operated for more than four to 12 hours per day, depending on the thickness of the freshwater lens and the amount of recharge.

regulation control, and improvements to the productivity of water used, although politically challenging demand management from a technical perspective may be the simplest and most cost-effective way to reduce water deficits and excess (waterlogging), particularly when water use is characterized by low efficiency.

As much as 80 percent of water used by a city is drained as sewage. If this can be treated in a cost-effective manner, 50 to 60 percent of this water could be recirculated or made available for other uses, which would significantly decrease the demand on groundwater resources. Treated waste water can also be considered as a source of artificial recharge water for groundwater, particularly in coastal areas where it may be used to prevent seawater intrusion (Herndon and Markus 2012). However, the geochemistry of both the recharge water and the receiving environment need to be well understood (El Arabi and Dawoud 2012).

MAR features in the National Water Policy 2018 and is aimed at artificially enhancing groundwater recharge to increase supply. The unintentional augmentation of groundwater by canal leakage and excess irrigation has been the principal source of Pakistan's groundwater for decades, and this experience could be built upon and formalized as part of an expanded MAR strategy for the Indus basin. The technical feasibility of such a scheme has already been considered by some authors. For example, Basharat and Basharat (2019) investigated recharging Bari Doab through the abandoned Sukh-Beas Channel. As long as storage options exist, MAR can be a solution for interseasonal storage, storing water during peak flow season (Kharif), and using it during minimum flow season.

MAR has attracted increasing policy support in India and Bangladesh, and a variety of structures can be deployed, including surface techniques (such as flooding, ditches and furrows, recharge basins, and runoff conservation structures) and subsurface techniques (such as injection wells, gravity wells, and recharge shafts), as described in CGWB (2007). Reddy, Pavelic, and Hanira (2017) describe the potential for MAR to help manage flood waters in South Asia and emphasize the importance of institutional collaboration in this endeavor. MAR is also a technique that is used in defending against seawater intrusion (box 3.4), such as has been trialed in Bangladesh.[13]

Although eagerly promoted in South Asia, MAR requires a sound knowledge of the water balance, a close proximity in time and space of available water and available aquifer storage, and a recognition of the downstream impact of diverting water for groundwater recharge. It can, at best, provide only a temporary reprieve from long-term depletion if demand management is not also successfully implemented.

Responding to Climate Change

Once the building blocks of groundwater management are in place, so also are the tools for responding to climate change. Many local and regional techniques can be deployed to help offset and manage the effects to groundwater of climate change (World Bank 2020). However, none of these techniques can be effectively deployed in the absence of a robust governance and management framework.

Managing Groundwater Quality

Tackling groundwater quality poses a significant challenge, whether measuring and tracking the problem, treating the water, or remediating the host aquifer. Once the groundwater system has been characterized and its behavior is understood, the frequency of water-quality data collection can be defined by risk analysis, such as which parameters are most likely to occur and what causes them to change adversely. A risk-based approach to tackle this problem—and to help prioritize control of the pollution (stopping the source) and its management once it has already occurred—enables better targeting of the water quality-monitoring budget. Working with users and influencers to control land-use practices and effluent disposal are critical elements to arresting many of the sources of groundwater contamination and its management. If groundwater used for drinking is already contaminated, solutions include the deployment of alternative water sources and installing treatment facilities. Because groundwater-quality problems can be quite localized, initial identification of water-quality parameters and contaminant sources, and ongoing water-quality monitoring, are important components of a groundwater-quality management strategy.

Although national and regional examples of appropriate drinking water-quality standards exist (Pakistan's National Drinking Water Policy, Government of Pakistan 2009), as well as environmental standards for controlling the release of pollutants to the environment, regional examples of groundwater-quality management are partially successful.

Regulatory Instruments

A variety of regulatory instruments can be deployed for the management and control of groundwater use and to protect its quality. Most of these rely on measurements that are not commonly made in Pakistan and so are not immediately applicable across the whole of the Indus basin. However, they merit consideration for future implementation while jurisdictions in Pakistan are in the process of forming policies and legislation aimed at improving water management. Examples of these instruments are provided in table 5.1 and would best be considered for introduction in a phased manner over a span of many years and in combination with extensive communication, education, and consultation campaigns with stakeholders.

The need for better data on groundwater systems is the first step toward developing a better understanding of the condition of the resource and how it is deteriorating. It is considered unlikely that farmer behavior can be changed just by permitting and regulation, particularly when there are a number of ways to get around them. Even if regulations were to be introduced forthwith, many of them would not be implementable in the absence of robust and authentic data. The government of Punjab has passed a new Water Act (December 2019) that envisages rules for controlling water use. However, a genuine question is now raised about the information that will be used for regulation while existing data sets cannot provide the basis for sound regulation. Rules and regulations may be drafted within a few months but may be impossible to implement appropriately for several years.

TABLE 5.1. **Examples of Regulatory Instruments to Improve Groundwater Management**

Regulatory instrument	Purpose	Comment
Geotag every groundwater extraction facility in an area	To commence a granular understanding of extraction locations to aid estimations of use	Prioritize critical areas before rolling out to whole CCA or province
Meter all groundwater extraction in an area	To understand volume of groundwater extraction	Prioritize critical areas and specific user groups (high water users, large farms, thirsty crops, tube wells above certain dimensions)
License all groundwater extraction in a management area	To limit the volume taken by individual farmers	• Can be done only after metering is introduced • Is likely to be disputed in the absence of an estimated sustainable yield for the management area or evidence of depletion • Prioritize critical areas and/or specific user groups first
Impose a tariff on extracted groundwater Make tariff-free in certain cases	• To discourage groundwater use in depleted areas • To encourage groundwater use where water table is high	• Can be done only after metering is introduced • Prioritize critical areas and specific user groups first • Tariffs can be structured to manipulate desired usage pattern
Create a register and licensing system for well drillers, supported by a training program	• To control and help protect groundwater infrastructure and quality • To assist in collecting data on new structures	Particular attention could be given to training for • Drinking water sources; and • Specialist infrastructure, such as skimming or scavenger wells
Require well diggers and drillers to report location and details of each new infrastructure	To understand the location and characteristics of infrastructure	Details to include description of strata encountered with depth, well construction (depth, diameter, position of screens, gravel pack, and/or grouting information), pump details, and yield and quality of water
Limit the dimensions of the infrastructure (depth and diameter of tube well and pump capacity)	To control the amount of water that can be taken	Prioritize critical areas and specific user groups/ purpose (high water users, large farms, thirsty crops, tube wells above certain dimensions)
Ensure pumping headworks, wells, and tube wells are protected from fecal contamination	To protect groundwater from microbial contamination	• Ensure wells are sealed at the surface and with drainage away from them • Ensure appropriate hygiene is followed when using or servicing hand pumps • Ensure safe distance between latrine pits and wells/tube wells for drinking water
Control fertilizer and pesticide use	To protect groundwater quality	Outreach work with merchants, agricultural extension officers, and farmer groups
Control solid waste disposal	To protect groundwater quality	Work with local government extension officers and communities
Control industrial effluent disposal	To protect groundwater quality	• Introduce random inspection powers • Introduce significant penalties for breaches of disposal license

Note: CCA = cultivable command area.

In the ACIAR project (see box 5.1), a co-learning approach has been adopted to raise awareness of stakeholders (irrigation departments, researchers, and farmers). By providing good-quality temporal data on groundwater levels and salinity, stakeholders will be concerned and want changes to be made. As co-researchers in the study, farmers will have the opportunity to contribute to the development of suitable and acceptable solutions.

Notes

1. For more information, see the CGWB website at http://cgwb.gov.in/.
2. For more information, see http://groundwater.ucdavis.edu/SGMA/.
3. For more information, see https://projects.worldbank.org/en/projects-operations/project-detail/P158119.
4. For more information, see the MARVI website at http://www.marvi.org.in/home.
5. See the manual at http://cgwb.gov.in/AQM/documents/Manual%20on%20Aquifer%20Mapping.pdf.
6. For more details, see http://www.aquiferindia.org/ and https://aims-cgwb.org/index.php.
7. See, for example, http://blogs.worldbank.org/water/can-you-crowdsource-water-quality-data.
8. For more information, see the India-WRIS website at http://indiawris.gov.in/wris/.
9. For more information, see the National Hydrology Project website at http://nhp.mowr.gov.in/.
10. For more information, see the Andhra Pradesh Water Resources Information and Management System website at http://www.apwrims.ap.gov.in/.
11. See the Ganges River Basin model at http://cwc.gov.in/sites/default/files/ganga-river-basin-model-and-wis-report-and-documentation.pdf as an example of the data requirements for a large basin model.
12. For more information, see the Lower Burdekin Catchment Story, *WetlandInfo* 2018, Department of Environment and Science, Queensland, Australia (accessed February 26, 2020), https://wetlandinfo.des.qld.gov.au/wetlands/ecology/processes-systems/water/catchment-stories/transcript-lower-burdekin.html.
13. For more information, see http://gripp.iwmi.org/natural-infrastructure/water-quality-2/a-nature-based-innovative-and-low-cost-solution-for-disaster-resilient-drinking-water-supply-in-coastal-bangladesh/.

References

ACE (Associated Consulting Engineers), EGC (Engineering General Consultants), and SMEC International. 2011. Nationwide Study of Groundwater Availability and Conjunctive Management. Volume 1. Ministry of Water and Power, Project Management and Policy Implementation Unit, Government of Pakistan. Lahore.

ACIAR (Australian Center for International Agricultural Research). 2016. “Improving Ground Water Management to Enhance Agriculture and Farming Livelihoods in Pakistan.” FAC Sheet, ACIAR, Canberra. Accessed November 2019. https://cdn.csu.edu.au/_data/assets/pdf_file/0011/2703845/Ground-_Water_FAC_sheet.pdf.

Ashraf, M ; Zeeshan, A. Bhatti ; Zakaullah. 2012. “Diagnostic Analysis and Fine Tuning of Skimming Well Design and Operational Strategies for Sustainable Groundwater Management - Indus Basin of Pakistan.” Irrigation and Drainage, 2012-04, Vol.61 (2), p.270-282

Basharat, M., and M. Basharat. 2019. “Developing Sukh-Beas as a Potential Recharge Site during Wet Years for Bari Doab.” *Applied Water Science* 9: 163. https://doi.org/10.1007/s13201-19-041-6.

CGWB (Central Ground Water Board). 2007. *Manual on Artificial Recharge of Ground Water*. New Delhi, India: Government of India Ministry of Water Resources CGWB. Accessed November 2019. http://cgwb.gov.in/documents/Manual%20on%20Artificial%20Recharge%20of%20Ground%20Water.pdf.

Chandio, A.S., and Lee, T.S. 2012. Managing Saline Water Intrusion in the Lower Indus Basin Aquifer. Water Resources Management 26, 1555-1576. https://doi.org/10.1007/s11269-011-9972-1

El Arabi, Nahed, E., and Mohamed A. Dawoud. 2012. "Groundwater Aquifer Recharge with Treated Wastewater in Egypt: Technical, Environmental, Economical and Regulatory Considerations." *Desalination and Water Treatment* 47 (1-3): 266–78. doi: 10.1080/19443994.2012.696405

Ensink, J. H. J., M. R. Aslam, F. Konradsen, P. K. Jensen, and W. van der Hoek. 2002. "Linkages between Irrigation and Drinking Water in Pakistan." IWMI Working Paper 46, International Water Management Institute, Colombo, Sri Lanka.

Evans, W. R., R. S. Evans, and G. F. Holland. 2013. "Conjunctive Use and Management of Groundwater and Surface Water within Existing Irrigation Commands the Need for a New Focus on an Old Paradigm." Thematic Paper 2: Groundwater Governance: A Global Framework for Country Action. http://www.groundwatergovernance.org/fileadmin/user_upload/groundwatergovernance/docs/Thematic_papers/GWG_Thematic_Paper_2_01.pdf

Government of India 2005. *Model Bill to Regulate and Control the Development and Management of Ground Water.* Ministry of Water Resources, Government of India, Delhi.

Government of Pakistan. 2009. *National Drinking Water Policy.* Ministry of Environment, Government of Pakistan, Islamabad.

——. 2018. *National Water Policy 2018.* Ministry of Water Resources, Government of Pakistan, Islamabad. Accessed April 2019. https://mowr.gov.pk/wp-content/uploads/2018/06/National-Water-policy-2018-.pdf.

Ground Water Resource Estimation Committee. 2017. *Report of Groundwater Resource Estimation Committee: Methodology.* Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India, New Delhi. http://cgwb.gov.in/Documents/GEC2015_Report_Final%2030.10.2017.pdf

Habib, Zaigham. 2010. *Policy and Strategic Lessons from the Evolution of Water Management in the Indus Basin of Pakistan.* The Planning Commission, Government of Pakistan. Islamabad.

Herndon, R., and M. Markus. 2012. *Large-Scale Aquifer Replenishment and Seawater Intrusion Control Using Recycled Water in Southern California.* Fountain Valley, California: Orange County Water District. Accessed November 29, 2019. https://www.ocwd.com/media/1857/large-scale-aquifer-replenishment-and-seawater-intrusion-control-using-recycled-water-in-southern-california.pdf.

HLPW (High-Level Panel on Water) 2018. "Making Every Drop Count: An Agenda for Water Action." Outcome Document, United Nations and World Bank Group, Washington DC. https://sustainabledevelopment.un.org/content/documents/17825HLPW_Outcome.pdf.

Jensen, P. K., W. van der Hoek, F. Konradsen, and W. A. Jehangir. 1998. "Domestic Use of Irrigation Water in Punjab" IN: Pickford, J. (ed). Sanitation and water for all: Proceedings of the 24th WEDC International Conference, Islamabad, Pakistan, 31 August-4 September 1998, pp.297-299.

Josset, L., M. Allaire, C. Hayek, J. Rising, C. Thomas, and U. Lall. 2019. "The U.S. Water Data Gap—A Survey of State-Level Water Data Platforms to Inform the Development of a National Water Portal." *Earth's Future* 7: 433–49. https://doi.org/10.1029/2018EF001063.

Lashari, B. K., and S. M. Kori. 2011. "Drainage Scavenger Tube Wells Can Sustain Rural Livelihoods: Evidence from Sindh Pakistan." In "Hydrological Cycle and Water Resources Sustainability in Changing Environments," Proceedings of IWRM 2010, Nanjing, China, November 2010.

Lashari, B. K., H. Ursani, M. Basharat, F. Steenbergen, M. Ujan, Z. Khero, N. E. Memon, S. Esin, A. W. Sheikh, M. A. H. Mahar, A. Bashir, G. Channar, A. Hussain, M. A. Mangrio, S. M. Kori, G. H. Wagan, S. N. Chandio, A. Muhammed, M. Ahmed, A. A. Detho, A. A. Mehmood, K. Ali, A. Jawad, A. Wahid, S. H. Memon, A. Mallah, C. Borgia, and S. Gohar. 2015. "The Promise of Conjunctive Management of Surface and Groundwater in Sindh." Shared Discussion Paper. *Meta Meta Groundwater Magazine*, January. http://metameta.nl/wp-content/uploads/2017/02/gwmagazines1_conjunctive_Sindh_LQ.pdf.

Petheram, Cuan, Keith L. Bristow, and Paul N. Nelson. 2008. "Understanding and Managing Groundwater and Salinity in a Tropical Conjunctive Water Use Irrigation District." *Agricultural Water Management* 95 (10): 1167–79. https://doi.org/10.1016/j.agwat.2008.04.016.

PPSGDP (Punjab Private Sector Groundwater Development Project). 2000. "Groundwater Management and Regulation in Punjab." Draft Technical Report No. 45, prepared by Groundwater Modelling Team of Punjab Private Sector Groundwater Development Project, Project Management Unit, Irrigation and Power Department, Government of Punjab, Pakistan.

Punthakey, J. F., A. A. Khowaja, and S. A. Prathapar. 1997. *Health and Irrigation Management in Sindh - Issues and Research Priorities.* Consulting Report for International Irrigation Management Institute, Pakistan.

Qureshi, A. S., and A. Sarwar. 2009. "Managing Salinity in the Indus Basin of Pakistan." *International Journal of River Basin Management* 7 (2): 111-17

Qureshi, Asad Sarwar. 2011. “Water Management in the Indus Basin in Pakistan: Challenges and Opportunities.” *Mountain Research and Development* 31 (3): 252–60.

Ravenscroft, P., K. J. Anandha Kumar, and Raja Ram Purohit. 2019. “Beyond GEC: Expanding the Horizons of Groundwater Assessment in India.” In Proceedings of the 2nd International Conference on Sustainable Water Management, Government of Maharashtra, Pune, India. November 6–8.

Reddy, V. R., Paul Pavelic, and M. A. Hanjra. 2017. “Underground Taming of Floods for Irrigation (UTFI) in the River Basins of South Asia: Institutionalising Approaches and Policies for Sustainable Water Management and Livelihood Enhancement.” *Water Policy*. (Online first). 20 (2): 369–387. doi:10.2166/wp.2017.150.

Saeed, M. M., and Ashraf, M. 2005. Feasible design and operational guidelines for skimming wells in the Indus Basin, Pakistan. Agricultural Water Management, 74:1-24.

Shalsi, S., C. M. Ordens, A. Curtis, and C. T. Simmons. 2019. “Can Collective Action Address the ‘Tragedy of the Commons’ in Groundwater Management? Insights from an Australian Case Study.” *Hydrogeology Journal* 27 (7): 2471–83.

Steenbergen, F., M. Basharat, and B. K. Lashari. 2015. “Key Challenges and Opportunities for Conjunctive Management of Surface and Groundwater in Mega-Irrigation Systems: Lower Indus, Pakistan.” *Resources* 4: 831–56. https://www.mdpi.com/2079-9276/4/4/831.

World Bank. 2005. “Review of the Performance of the Left Bank Outfall Drain Stage I (KPOD, DPOD, Tidal Link and Cholri Weir).” Report of the World Bank International Panel of Experts, South Asia Region, Agriculture and Regional Development, World Bank, Washington DC.

———. 2006. “Integrated River Basin Management: From Concepts to Good Practice.” Briefing Note 7, World Bank, Washington DC. http://documents.worldbank.org/curated/en/742551468320657959/pdf/411560River0ba1ning0NOTE1701PUBLIC1.pdf.

———. 2020. “Managing Groundwater for Drought Resilience in South Asia.” World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/33332

Chapter 6
Conclusions and Recommendations

Key Points

- Groundwater in Pakistan's Indus basin currently provides more than half the irrigation water for Punjab and the majority of the country's drinking water.
- Groundwater management in the basin is inadequate, and the growing disbenefits of poor water management will retard economic and social progress.
- Institutional collaboration and reform are fundamental to basin planning and to maximizing the value of Pakistan's groundwater resource.
- There are solutions to Pakistan's groundwater challenges, and a portfolio approach is recommended.
- Groundwater challenges in the Indus basin require cross-sectoral and multitier interventions.
- Data collection must be at the resolution and integrity needed for robust planning to form the foundation of effective groundwater management in the Indus basin.

Conclusions

Pakistan's Indus basin aquifer underlies about two-thirds of the country and holds in storage a vast volume of fresh water. This globally important water resource has resulted in a doubling of cropping intensity within much of the world's largest contiguous irrigation network and provides most of the country's drinking water. The groundwater contribution to irrigation and water supply has enabled decades of growth and development.

Domestic and industrial use are currently the fastest-growing groundwater demand sectors. Domestic water demand in Pakistan is set to double by 2050, and deteriorating groundwater quality (including from salinity, microbial pollution, natural contaminants, such as arsenic and fluoride, and industrial pollutants) is an increasingly urgent issue with the majority of drinking water in the country contaminated and little evidence that the problem is being addressed.

Agriculture uses more than 90 percent of Pakistan's groundwater but delivers very low agricultural water productivity. Overabstraction of groundwater in some parts of the country threatens continued use of groundwater and increases abstraction costs, whereas in other areas an excess of irrigation has led to waterlogging and soil salinization problems. Low agricultural productivity presents a considerable opportunity for efficiency gains and reallocation of water resources to higher-value sectors. However, the lack of reliable and accessible data on groundwater conditions and use limits the creation of a solid management foundation and constrains policy options.

Although identified as a provincial role, the collection and analysis of groundwater data are conducted to a similar or greater extent by the federal government, and both tiers of government have a legitimate interest in groundwater.

The National Water Policy 2018 acknowledges the importance of groundwater to Pakistan's economy and highlights the country's increased attention to integrated water resource management. This is an important advance on the current approach that, through sectoral and institutional segregation, overlooks the large overlap between surface water and groundwater resources. However, there remains a lack of clarity about which are the responsible institutions in each tier of government; therefore, there is no accountability. As a result, across different sectors and among different tiers of government, groundwater management is being considered in the abstract, yet there is a failure in clear allocation of roles and responsibilities and in coordination among all these agencies. The resulting failure to collect reliable data has an ongoing adverse impact on Pakistan's ability to adequately provision for the increasing water demand in every sector. The outcome is a fragmented understanding of the trajectories of groundwater performance (level and quality) in different parts of the country and of the implications of these trajectories for different sectors. Inadequate knowledge is matched by infrequent and poorly targeted interventions aimed at tackling one issue without taking account of interlinked water and land management issues. Such an approach is unlikely to solve even one problem, let alone the network of interlinked challenges that demand management attention. Authentic data on static and dynamic groundwater conditions provide a basis for basin-scale modeling of the resource, including numerical modeling and coupled transport modeling of contaminants.

The identified technical and institutional challenges facing groundwater management in Pakistan's Indus basin are all clearly stated in the National Water Policy 2018 and are no different from those raised by many authors since the 1960s. These challenges are common with other countries that share the aquifers of the interconnected Indus, Ganges, and Brahmaputra river basins. The advantage of these shared challenges is that solutions, if not already deployed in Pakistan, are available from within the region and likely to be adaptable to local conditions. The reform path is an adaptive process and should therefore be seen as part of a continuum that, for successful implementation, must be inclusive and composed of multiple steps.

Recommendations

Given the great value of the Indus basin aquifer to the Pakistan economy, and to the health and well-being of the majority of its population, a renewed focus on groundwater is warranted. Attention on data and information, combined with institutional support and reform, promises to deliver improvements to the management of this resource that will benefit the whole country. The cost of such planning interventions is likely to be significantly less than the increasing economic burden and health outcomes of poorly coordinated and unplanned groundwater use.

The recommendations here represent the four principal blocks of activities that are considered of equal status—and essential to ensure a new era of responsible groundwater management in Pakistan.

Recommendations for Institutional Reform

Create institutional accountability at both the federal and provincial levels to satisfy agreed responsibilities for managing groundwater.

Ensure community participation is at the heart of institutional reform.

Create an effective coordination mechanism for groundwater management at the provincial level that provides the link among government sectors and tiers of government, including to the local community level. Groundwater projects conducted by the federal government must be conducted in close coordination with provincial governments and with the aim of building capacity in the provinces. The purpose of this coordination is to remove overlaps and gaps in groundwater management and to ensure a common goal for interventions.

Create interim arrangements until permanent ones can be put in place so that the most pressing groundwater issues can start to be addressed immediately. This might include the establishment of a temporary unit that is tasked with establishing the framework for groundwater management across the province. It can be staffed by secondees from the different sectors of provincial government. If capacity is low, support from the federal government should be available. Following the long-term institutional reform, the interim unit can then be disbanded but its members remain connected through intersectoral communities of practice that ensure that coordination continues and is encouraged between nascent lead groundwater management agencies and their stakeholders.

Recommendations on Data for Integrated Basin Planning and Resource Management

Federal and provincial governments must agree on the support mechanism for groundwater data. Its institutional home and budget provision should reflect the value of the data to the sectors, the province, and the nation. Data management systems used by different provinces and the national government need to be interoperable.

Create cross-sectoral and cross-jurisdictional coordination and agreement on roles and responsibilities for data collection, curation, and storage. There must be collaboration on protocols to ensure common standards of data and its integrity to include the appropriate calibration and maintenance of all field equipment, the procedure adopted to confirm data authenticity, and a common decision on the management information system to house the data. These activities should include an interim protocol for digitizing older data still held in field notebooks—an activity that, if done thoroughly (for example, cross-referencing data sets to confirm data reliability), has the potential to provide important insights into system dynamics that will provide context for the understanding of current measurements and support to planning efforts.

Build capacity for improving groundwater data collection in the provinces. The distributed nature of monitoring locations calls for community-level involvement, combined with innovative techniques to maintain the essential skills and discipline required to ensure data integrity. Establishing communities of practice that link experts to field technicians and data users (including research agencies) would be one way to support innovation and knowledge sharing in data collection techniques.

Develop local water resource plans as essential building blocks for a national basin plan, taking all water (including drainage and wastewater) and land use into account. Plan development requires the same cross-sectoral and multitiered approach as for data collection. Water resource planning is a multiscale activity, from the basin to the canal command level, to the distributary and farm scale. It must link with community-scale initiatives as well as the wider provincial and national socioeconomic and environmental policies and should be aligned with Pakistan's broader spatial and economic planning framework.

Recommendations on Conjunctive Management for Waterlogging, Depletion, and Salinity Control

Apply management principles to existing conjunctive use. This means rebalancing the use of groundwater and canal water at the command level so that water inputs and outputs are measured and controlled (including canal deliveries, irrigation application, and drainage management).

Calculate water budgets for all water in each management area. The budget needs to account for both supply (inflow) and demand elements—and the seasonal influence on both. It will require stakeholder and expert input on budget estimation and on how and where to apply management interventions to rebalance the budget.

Apply controls to water inputs and outputs: Manage the delivery of water through the canal system in conjunction with the extraction of groundwater such that if water tables are high and groundwater is fresh (at canal heads, for example), this should be used exclusively for irrigation so that canal water can be saved for downstream users in areas where groundwater is saline. Such an approach requires extensive outreach work with affected landholders and suitable incentives to encourage a change in behavior. Similarly, the drainage of waterlogged areas must be enhanced to liberate currently barren land for agricultural use and to allow the flushing of saline soil.

Managed aquifer recharge (MAR) is recommended for areas of depletion where there is a clearly identified source of recharge water and suitable recharge sites and where the tradeoffs, particularly downstream impacts, are well understood. This technique is management intensive and should be accompanied by demand management to help guarantee the long-term sustainability of MAR schemes.

Recommendations for Managing Groundwater Quality

Adopt a risk-based approach to prioritize activities for groundwater quality management. Such an approach includes baseline measurements of quality parameters and an evaluation of the severity and extent of harm caused by the quality impairment. It can be applied both to preventing groundwater pollution and to managing it once it has occurred.

Control the source of anthropogenic contamination from liquid waste (agricultural drainage, industrial effluent) fecal matter and solid waste to prevent further groundwater contamination. This means extensive community engagement to ensure that all effluents and solid waste are managed in appropriate facilities and the application of agricultural chemicals are controlled. Although the cost and political challenge of achieving these may be significant and the need for community outreach extensive, these should be set against the financial burden and effort of decades-long groundwater remediation and associated treatment requirements as well as the cost of long-term health impacts resulting from ongoing release of these contaminants.

Manage geogenic contamination, such as arsenic and fluoride, by detailed sampling campaigns for drinking water schemes and mapping their presence to understand exactly with which strata they are associated. In places where there are no options other than to use groundwater containing geogenic contaminants, treatment options exist at multiple scales and must be deployed where this kind of water is used for drinking.

Manage groundwater salinity by monitoring the spatial distribution (laterally and vertically) of saline water and fresh water and the temporal changes of the interface between the two water types; modifying pumping rates and volumes to minimize disturbance of the saline layer; and using skimming wells to help maximize the use of fresh groundwater while avoiding its contamination with saline water. It is important that all groundwater pumping is controlled in such an area as just one rogue pumping action can contaminate the aquifer for all users. In coastal areas, MAR schemes can be considered to resist seawater intrusion. **It is recommended** that regular preventive and predictive water quality monitoring be conducted to understand how the presence of contaminants is changing with time. The results of such campaigns will help define essential groundwater management criteria and identify treatment requirements where health-related contaminants are present in groundwater used for drinking. National studies already conducted by the Pakistan Council of Research in Water Resources (PCRWR) can help in developing the risk-based approach to prioritizing the sequencing and frequency of groundwater monitoring in the Indus basin.

Implementation

Institutional reform and resource planning are complex tasks anywhere in the world and require coordination across multiple stakeholders and sectors. Given the state of groundwater management in Pakistan and the country's federal structure, multiple interventions across different tiers are required. Derived from the broad management principles described in chapter 5 the current understanding of the Indus basin aquifer, and the challenges faced by Pakistan detailed in this report, management recommendations fall into four main areas, as shown in figure 6.1, each of which requires consideration at various levels of policy, practice, and governance. Every action within each of these components represents an important advance along the road map to reform. More details are provided in appendix D, which provides stepwise guidance on implementation of these technical, policy, and institutional measures.

FIGURE 6.1. **Recommendations for Improved Groundwater Management in Pakistan**

Institutional reform and regulation

- Appoint provincial lead agencies and agree on scale of management
- Regulatory reform
- Interim management arrangements
- Stakeholder/community engagement

Conjunctive management, waterlogging, salinity, and depletion

- Develop water budgets for management areas
- Closely monitor water balance to ensure irrigation deliveries do not exceed drainage capacity
- Demand management and managed aquifer recharge
- Stakeholder/community engagement

Data for integrated basin planning and resource modeling

- Lead Agency responsible/accountable for data
- Structured capacity building and development of data architecture
- Consolidated surface water and groundwater data (static and dynamic data)
- Data sharing with managers and users

Managing groundwater quality

- Identification of local water quality parameters and regular water quality monitoring
- User participation to monitor and control land use practices and effluent disposal
- Treatment of drinking water
- Data sharing with managers and users

Appendix A
Details of Previous Groundwater Studies in Punjab and Sindh

This appendix provides details on important studies and on groundwater models developed for the Indus basin.

Groundwater Models in Punjab

Although there are few modeling studies that cover the entire Indus basin, a number of groundwater models have been developed in parts of it. The studies documented in this review are either at the doab scale or at the canal command level, or they focus on specific issues on a much smaller scale. Of these, the most recent work covers the Rechna Doab model developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) and the International Water Management Institute (IWMI) (Khan et al. 2003), the Upper Chaj Doab model (Ashraf and Ahmad 2008), the Lower Bari Doab (Basharat 2012; Lahmeyer International and National Development Consultants 2013), and the revised Rechna Doab model that was developed in conjunction with Pir Mehr Ali Shah - Arid Agriculture University Rawalpindi (UAAR)[1] and the Punjab Irrigation Department (PID) on an Australian Center for International Agriculture Research (ACIAR) project (Punthakey et al. 2015). A modeling study is also being undertaken for part of the Lower Bari Doab under an ACIAR project, the results of which are expected to be available in October 2020. The modeling reviews provide an overview of the state of knowledge based on modeling studies in Punjab. Although some of the studies may be dated, each provides useful knowledge for future studies, which will need to be undertaken to support Punjab water policy. They also indicate the data availability and constraints under which these models were developed.

The lessons that can be drawn from these studies are: (a) development of groundwater models should follow modeling guidelines that can be used to guide or support policy makers and regulators; (b) accurate spatial and temporal monitoring of groundwater resources is essential for robust groundwater models; (c) modeling objectives need to be clearly defined and models updated at regular intervals to ensure predictions are relevant; (d) detailed water balances should be presented that allow estimation of sustainable yield; (e) the limitations of models and model predictions must be clearly understood; (f) models need to be updated on a regular basis as additional data become available; and (g) groundwater models also provide foresight into expected impacts on the resource of climate change and management responses.

Models of Doabs and Smaller Scale Studies

A finite element model was developed to analyze the regional groundwater flow of the Upper Chaj Doab area in the Indus basin and to estimate the groundwater budget of the aquifer (Ashraf and Ahmad 2008).

The transient model was run from 1985 to 2005 and scenarios simulated to 2020. Modeling results show a gradual decline in the water table from 1999 onward. The persistent dry condition and high withdrawal rates have resulted in lowering groundwater levels. The declines predicted by the model were because of increased pumping during drought conditions from 1999 to 2002. It is likely that wetter conditions over the past 10 years and particularly the floods during the 2010 monsoon may have reversed some of these declines. This indicates the importance of updating models regularly to ensure that predictions are relevant.

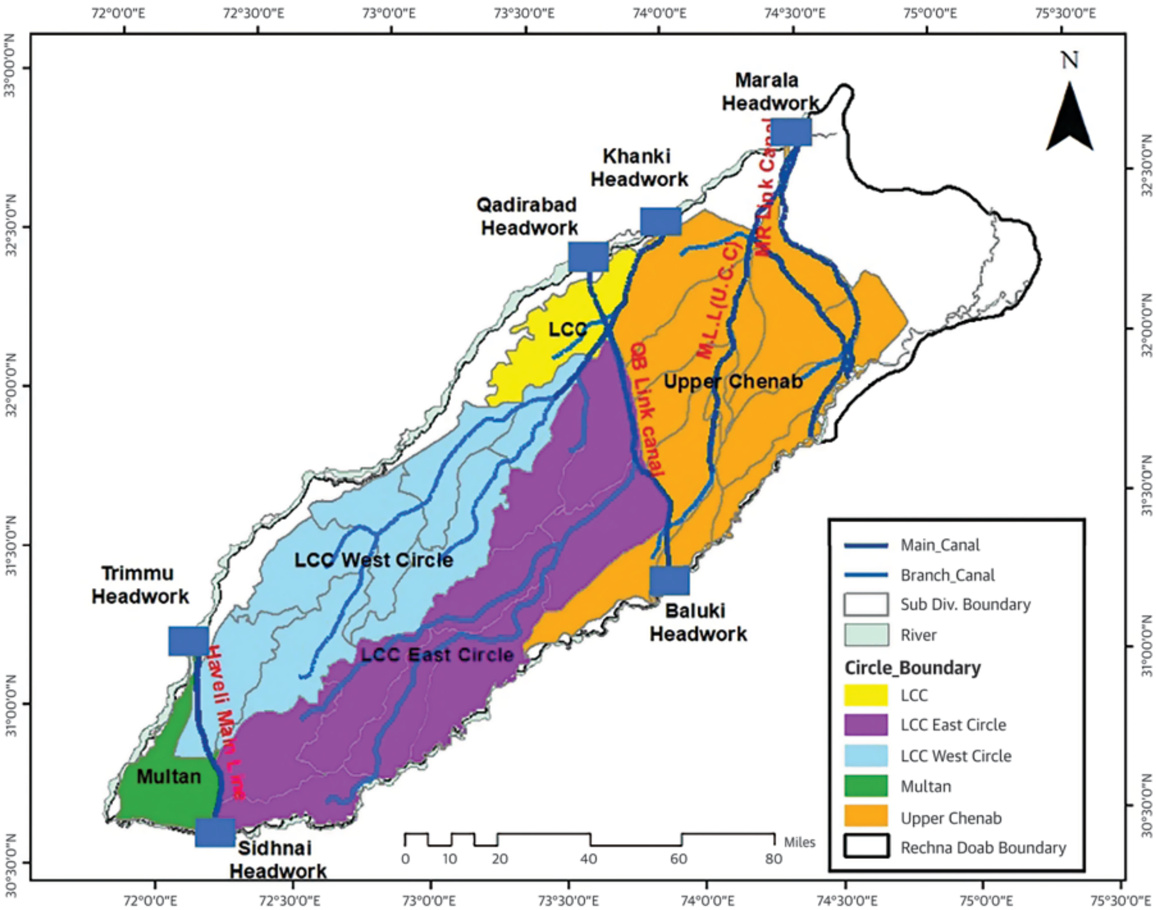
Groundwater studies have been undertaken in the Rechna Doab by groups including the International Water Logging and Salinity Research Institute (IWASRI), the PID, and various academics. An early study was the development of a regional lumped water balance model to estimate recharge for Rechna Doab on a seasonal basis for a period of 31 years (1960-90). The average value of net groundwater recharge during Kharif (April to September) season was estimated at 60 millimeters, whereas for Rabi (October to March), the groundwater reservoir was depleting. Long-term average annual depletion of the groundwater reservoir was found to be greater than corresponding recovery from annual recharge. Their study concluded that regional groundwater levels in Rechna Doab had declined by 2.3 meters over the 31-year period—an average decline of 74 millimeters per year. This finding is supported by the increase in the number of private tube wells for irrigation from a few thousand in 1960 to 340,000 in 1990.

The Rechna Doab (CSIRO-IWMI) model, developed by Khan et al. (2003), used data from 1992 to 1999. This model indicated that if dry conditions persisted, groundwater levels would decline by 10 meters across the Doab over the next 25 years. In addition, the lower parts of Rechna Doab with limited surface water supplies would undergo the highest decline in groundwater levels (10 to 20 meters), which would substantially increase the cost of groundwater pumping for farmers.

However, a more recent modeling study in Rechna Doab (Punthakey et al. 2015), developed using monthly stress periods from 2008 to 2014, found the doab was a relatively resilient groundwater system with stable water tables. This model's results indicated that the upper Rechna Doab water tables were steady or gradually rising (less than 1 meter), whereas in the lower Rechna Doab, water levels were either stable or showing a gentle decline (less than 1 meter). In this model, recharge from rainfall and irrigation was a significant component of recharge to the aquifer followed by canal seepage, which allows the system to be reasonably resilient despite very high extraction of groundwater. The groundwater and solute transport model was developed using the PID's extensive data set on water levels and salinity, which have been monitored since 2008. The monitoring of salinity from several hundred tube wells undertaken by PID staff in Rechna Doab provided a valuable data set. Salinity of the groundwater can range from 2,000 to 5,000 microsiemens per centimeter in the mid-regions of the doab and at the tail ends of canals. The risk of increasing salinity of freshwater zones from saline intrusion and upconing from deeper saline layers as a result of sustained pumping poses an additional risk, which is common in the mid-regions of doabs.

A sub-model comprising the Lower Chenab Canal East (LCC-East; see map A.1) region, Punthakey et al. (2015) found 68 percent of inflows were from irrigation and rainfall recharge and the remaining

MAP A.1. **Canal Irrigation Network in Rechna Doab, Punjab, Showing Canal Commands**



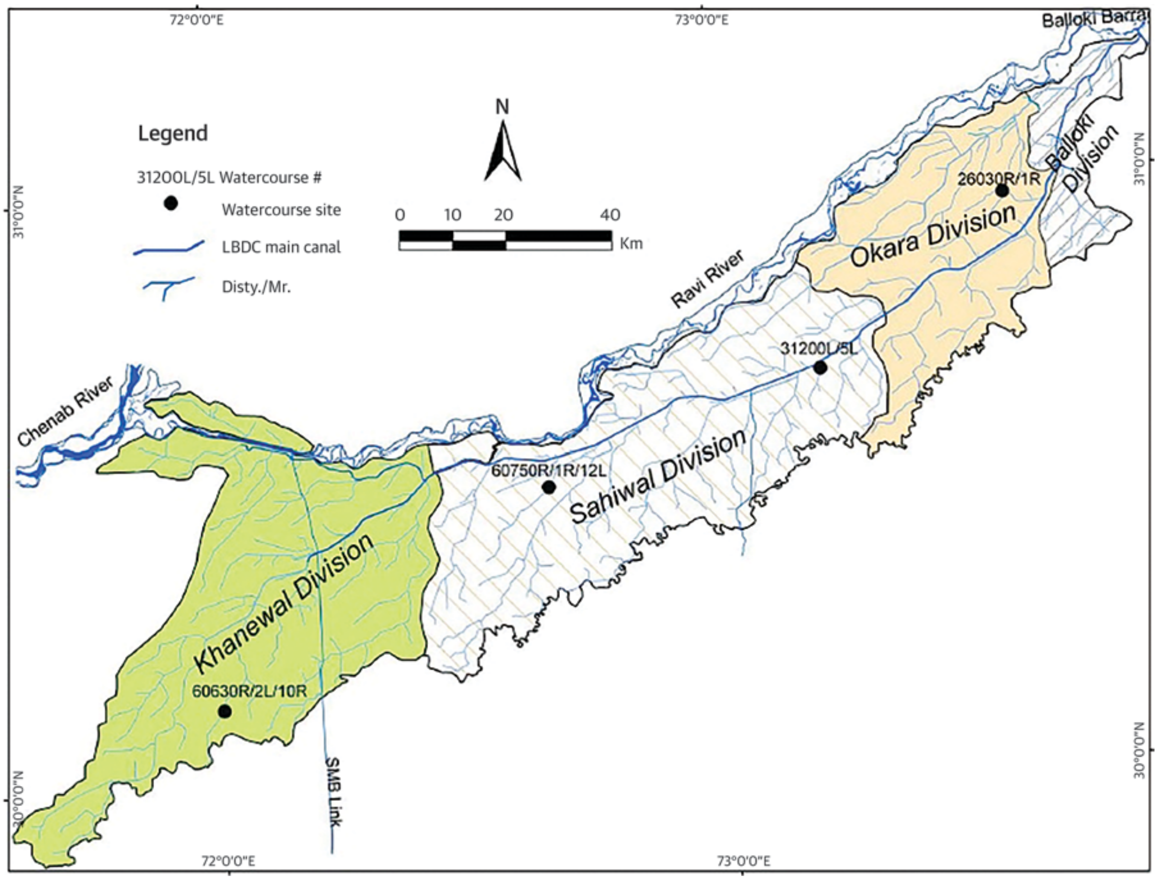
32 percent from canal seepage and inflows from Upper Rechna Doab. Pumping was 56 percent of total inflows, which means pumping could be increased; however, this would increase the risk of induced salinization as the underlying groundwater in LCC-East is saline.

The Lower Chenab Canal West (LCC-West, see map A.1) model was developed by Shakoor et al. (2018). Scenario runs to 2030 indicated that if groundwater extraction were to continue at the current rate, the maximum water-level decline would be 14 meters. Using the historical year-on-year increase in pumping, the maximum water-level decline would be 18 meters. Modeled responses to reducing canal supplies and increasing pumping in the upper part of the model, and increasing canal supplies and reducing pumping in the mid-portion of LCC-West, allowed recovery in groundwater levels by 2 to 3 meters in the middle part of the study area. The authors concluded this would be a good management strategy for LCC-West as it would allow partial recovery in groundwater levels in the mid-portions of the model and minimize waterlogging in the upper parts of LCC-West.

A model covering an area of 38,100 hectares between the Qadirabad Balloki Link Canal and Upper Chenab Canal in the Rechna Doab was developed by Sarwar and Eggers (2006) to evaluate alternative management options for surface water and groundwater resources. The model was applied to predict groundwater levels up to 2010 in response to the possible need for intervention in irrigation and/or agricultural practices. The study found that pumping for a cropping intensity of 130 percent would result in water tables falling by 4.17 meters, whereas an increase in pumping for a cropping intensity of 150 percent would result in declining groundwater levels up to 6.57 meters.

A study undertaken by Arshad, Ahmad and Usman (2009) estimated seepage from the Upper Gogera Branch Canal in the Rechna Doab at an average monthly rate of 12.1 $m^3/s/km^2$ (meters cubed/second/square kilometer) for a monthly average flow rate of 106 m^3/s. Seepage contribution to groundwater ranged from a low of 1425 $m^3/d/100$ meters of canal length during February 2003 to a high of 1942 $m^3/d/100$ meters of canal length during July 2003. An empirical relationship between seepage (S) and the canal flow rate (Q) was developed ($S = 0.006*Q^{1.44}$) to quantify the seepage to groundwater from the canal for any flow rate.

MAP A.2. Lower Bari Doab Showing Irrigation Divisions and Selected Water Courses



Source: Basharat 2012.

A model of the Lower Bari Doab Canal command (see map A.2) (Basharat 2012; Basharat and Tariq 2013) was used to evaluate long-term irrigation cost inequities as a result of increasing groundwater depletion toward the tail end. The model was calibrated over a period of eight years from Kharif 2001–09 with seasonal time steps (Kharif and Rabi). The total recharge (including groundwater returns) for 8.5 years is 23.45 million acre-feet, and tube well abstraction is 27.02 million acre-feet. Values per year for these two parameters are 2.759 million acre-feet and 3.178 million acre-feet, respectively, showing that groundwater abstraction is higher than the recharge to the aquifer. The groundwater budget component as a result of evaporation is relatively less because of the water table being deep in most of the command areas (Basharat and Tariq 2013). Decreasing rainfall and increasing crop water requirement toward the tail end is resulting in greater groundwater depletion downstream from canals, particularly at the tail ends.

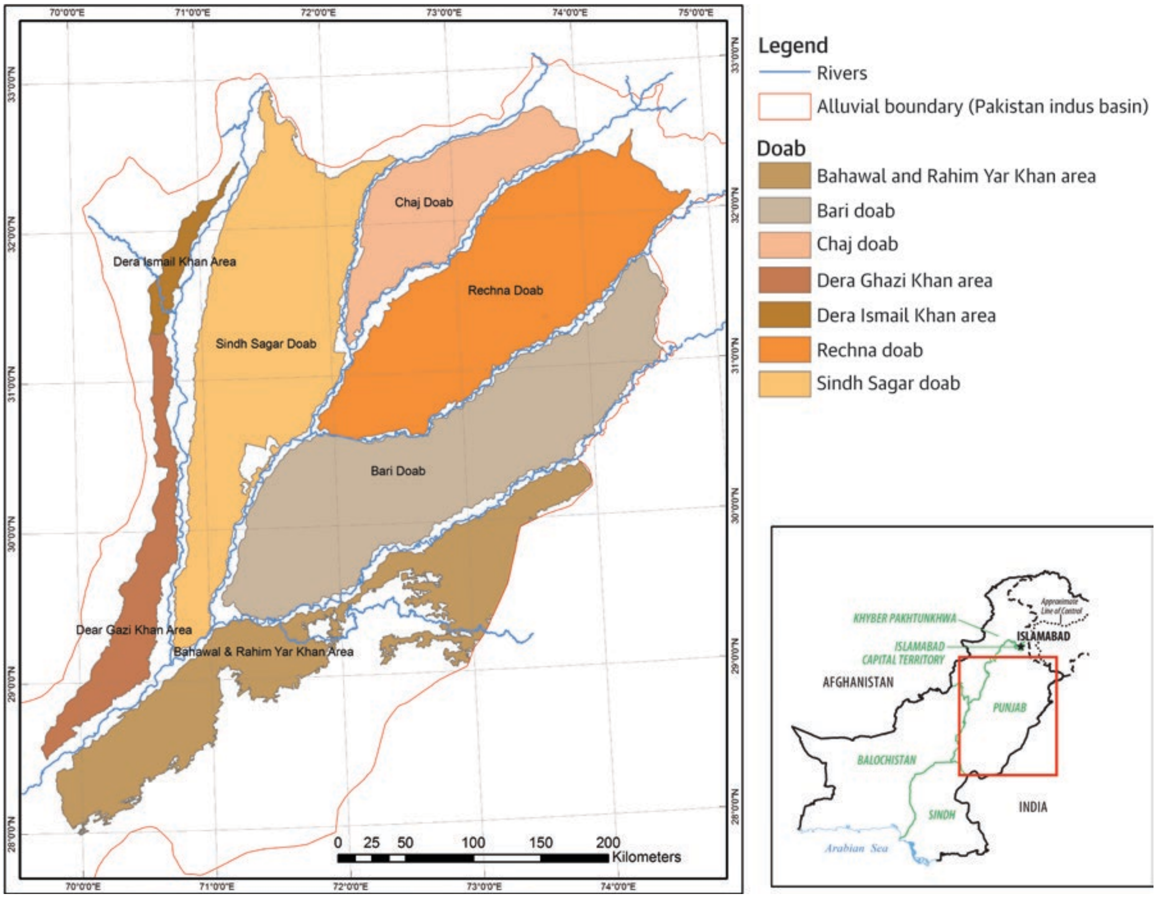
The Lower Bari Doab Canal (LBDC) model developed with funding from Asian Development Bank as part of the Lower Bari Doab Canal Improvement Project (LBDCIP) (Lahmeyer International and National Development Consultants 2013). Groundwater quality data for the LBDC command analyzed from 1995 to 2012 found the area with fresh groundwater resources reduced from 71 percent in 1995 to 32 percent in 2012. The area with marginal groundwater quality increased from 22 percent in 1995 to 49 percent in 2012. The area under hazardous water quality increased from 7 percent in 1995 to 19 percent in 2012. The trend over those 17 years is that groundwater quality in the LBDC command is generally deteriorating. In some areas near the Ravi River and along the main canal, the electrical conductivity (EC) of groundwater declined, whereas in areas away from the Ravi River and toward the center of the doab, the EC of the groundwater increased. This finding is consistent with current understanding of salinity dynamics in the other doabs.

The LBDC model was used to determine the impact of different scenarios of canal water availability and groundwater abstraction on surface water and groundwater resources in the LBDC. The main finding from the scenario runs showed that reducing tube well pumping and increasing canal water supplies seem to be the only effective ways of arresting the current pace of groundwater drawdowns in large areas of the LBDC.

The models at the doab scale are useful for the irrigation department to improve planning and management of surface water and groundwater resources. As the share of surface water decreases and groundwater levels continue to decline in the lower regions of the doabs, there will be increased pressure on government agencies to find socially and technically acceptable solutions as well as giving due consideration to environmental needs. Provincial agencies can utilize scenario modeling to identify and select suitable options by predicting groundwater response to specific interventions and management. This will require increased capacity of irrigation agencies as well as institutional reform to manage and regulate groundwater resources.

The models in this review are developed using limited data sets over a few years. For robust modeling, the irrigation departments need to extract useful information from various studies and develop models that can be updated at regular intervals for improved planning and management of the resource. Models can be incrementally improved through regular updates and verification using independent data sets.

MAP A.3. Location of Doabs in Punjab



Subregional Model of the Doabs of Upper Indus Plain Aquifer

Groundwater models were developed by the Pakistan Council of Research in Water Resources (PCRWR) for each of the four doabs (map A.3) in the upper Indus Plain: Bari, Chaj, Rechna, and Thal (Khan, Iqbal, et al. 2016). The aims of these models were to provide information on spatial patterns of groundwater flow, identify sources of groundwater recharge, account for surface water-groundwater interaction in each doab, and develop strategies for sustainable groundwater management in the upper Indus plain aquifer. The models predicted an increasing trend in simulated heads (1.6 meters) for Upper Thal Doab and a decreasing trend in Central Thal Doab (0.6 meters) over the calibration period from 1984 to 2009. However, simulated heads for Upper Thal Doab from 2009 to 2025 show a decline of 4 meters. Isotopic analysis further showed that the Upper Thal Doab received significant recharge from the Indus River. In Central Thal Doab, the contribution to recharge from both the Indus and Jhelum rivers is significant partly because of sandy soils and seepage from canals. Parts of Lower Thal Doab experience waterlogging as it is a narrow strip bounded by the Indus and Jhelum rivers.

The Chaj Doab is the smallest of the doabs and bounded by the Jhelum and Chenab rivers. The doab receives significant recharge from the bounding rivers, Mangla Dam, higher rainfall, and seepage from canals. Simulated heads show an increasing trend of 1.6 meters for Upper Chaj Doab and 1.1 meters for Lower Chaj Doab. The authors report that in Central Chaj, a combination of higher tube well density (0.18 per hectare) has resulted in significant depletion during 1984 to 2009, which was further aggravated by the severe drought from 1999 to 2002. Scenario analysis to 2025 shows an increasing trend in Upper and Central Chaj Doab and a decrease of 3.3 meters in Lower Chaj Doab.

The model for Rechna Doab predicted water level declines of 4.4 meters in Upper Rechna Doab and declines of 1.3 meters in Lower Rechna Doab. The authors attribute the former to reduced rainfall recharge, which is based on isotopic analysis, and further state that Upper Rechna Doab is not being recharged by rivers and irrigation system. This is somewhat counterintuitive. One would expect significant seepage from the main and link canals in the upper reaches of Rechna Doab given that the large Marala headwork, the Marala Ravi Link Canal, and the Bambanwala-Ravi-Bedian (BRBD) Canal go through the area. However, the central regions of Rechna Doab showed a rising trend of water tables by 1.6 meters. Additionally, as noted by Khan, Iqbal, et al. (2016), pumping from a large number of private tube wells (333,000) dominates the outflow from the aquifer in Rechna Doab. In the lower reaches of Rechna Doab, the authors point to a depletion of 10 to 20 meters for simulated water levels from 2002 to 2025 as a result of lower rainfall recharge, low flows in the Ravi, and excessive pumping.

Similarly, in the Bari Doab, a combination of low flows in the Ravi and Sutlej rivers and excessive pumping for irrigation results in a 4 meters depletion of water levels in the upper reaches of Bari Doab, a 1-meter decline for the central region of the doab, and a 3.2-meter decline in the lower regions of the doab. Khan, Iqbal, et al. (2016) suggest that the Upper and Lower Bari Doab are under stress because of an imbalance between recharge and pumping. Significant depletion in the Upper Bari Doab is attributed to excessive groundwater pumping in the city of Lahore. The increased dependence on groundwater for irrigation was also indicated by Basharat and Tariq (2013). Simulated results for the Lower Bari Doab model show the largest declines of 0.38, 0.24, and 0.18 meters per year for Multan, Lodhran, and Khanewal districts, respectively, between 2005 and 2025.

The report by Khan, Iqbal, et al. (2016) estimates the average safe yield for each of the doabs of the upper Indus plain aquifer as follows: Thal Doab (9 billion cubic meters per million hectares), Chaj Doab (8.7 billion cubic meters per million hectares), Rechna Doab (7.7 billion cubic meters per million hectares), and Bari Doab (4.5 billion cubic meters per million hectares). A suggested safe yield for the upper Indus plain aquifer of 7.5 billion cubic meters per million hectares is provided. The study reported a partial water balance based on recharge to the system. A detailed modeling and water balance report would be required to understand how the safe yield was derived. An earlier study by Punthakey et al. (2015), which modeled the Rechna Doab, reported a sustainable yield of 10.1 billion ± 1 billion cubic meters to allow for adaptive management for model calibration period of 2008 to 2014. The area modeled covered 2.92 million hectares. This equates to a sustainable yield of 3.46 billion ± 0.34 billion cubic meters per million hectares, as compared with 7.7 billion cubic meters per million hectares estimated by Khan, Iqbal, et al. (2016). A detailed comparison of water balances used by the respective models would help to explain the differences between the models.

A Subbasin-Scale Groundwater Model for Punjab

A groundwater model for the Punjab part of the Indus basin was developed using MODFLOW (Khan, Yang, et al. 2016). The rationale for developing this model is the need to understand groundwater dynamics at a subbasin scale. The groundwater system was conceptualized as a single-layer, unconfined aquifer with a thickness of 300 meters and grid cells of 1 square kilometer. The total groundwater abstraction across Punjab in 2001-02 was estimated at 43.4 billion cubic meters based on surveys of tube well density provided in the Punjab Statistical Handbook (Government of Pakistan 2012). For the scenario runs, the spatial density of tube wells was updated for 2011, which resulted in a total groundwater abstraction of 60 billion cubic meters (Yang et al. 2013) for a simulation period of 23 years, starting in October 2011. The main findings show the depth to water table under initial conditions is generally less than 10 meters in Punjab. However, at the end of 23 years of simulation under the status quo, the depth to water table is greater than 25 meters in some areas. The most significant decrease in heads is in northeastern Punjab, particularly in the Lahore division. The depth to water table is less (that is, water tables are higher) along the Jhelum, Chenab, and Ravi because the rivers recharge the aquifer. This finding is understandable for the Chenab and Jhelum; Ravi may need future investigation as it has little to no flow because of reduced flows in the eastern rivers. Inequities in canal water allocations result in inequities in pumping costs—farmers at tail ends of canals pay twice as much in pumping costs as farmers at the head ends. The various scenarios support a revaluation of the canal water allocation schedule, which can provide policy guidance.

Groundwater Studies in Sindh

As for Punjab, there have been extensive groundwater studies in Sindh, including the development of groundwater models, which are outlined in the following sections.

Lower Indus Project

The most significant of these early regional studies was undertaken by Hunting Technical Services (1966) for the Lower Indus Project (LIP) for the Water and Power Development Authority (WAPDA). The hydrogeology of the lower Indus basin was studied extensively, including a program of drilling, estimation of aquifer parameters, and water quality analysis of groundwater. This was a significantly important study on groundwater in Sindh and provides an assessment of the aquifer downstream of Kotri Barrage. However, there have not been any studies of this scale in other parts of Sindh.

The lower Indus alluvial complex forms a large, highly transmissive, unconfined aquifer system. According to the LIP report (LIP 1965 Vol. 6 GW), the thickness of the alluvium is not accurately known, though it exceeds 182 meters over large parts of the basin and is less than 61 meters only in small parts adjacent to bedrock outcrops, such as in Khairpur district. There are, however, some bores that have been drilled to more than 400 meters and still not reached bedrock (for example, bore LIPW117 in Khairpur district). This is consistent with the LIP report of a deep and highly transmissive aquifer system.

To determine aquifer parameters, 10 pumping tests were performed from Kotri to the sea. Tube well depths ranged from 43 to 91 meters (140 to 300 feet). The pumping tests in the LIP report estimated transmissivity of 159 to 440 square meters per day, with an average of 269 square meters per day; horizontal hydraulic conductivity of 19.5 meters per day; specific yield of 13 percent; and estimated vertical permeability of 0.045 meters per day. Although these tests were carried out downstream of Kotri Barrage, they give a good indication of the lower range of hydraulic conductivities (K). Horizontal K are less than half the K around Guddu Barrage, which was estimated at 52 meters per day in the LIP study (Basharat 2005), suggesting that it tends to decrease downstream.

Prior to introduction of the modern, weir-controlled irrigation system at Kotri Barrage, the groundwater regime was in dynamic equilibrium. Sources of recharge into the area were subsurface inflow from upper areas, seepage from river and inundation canals, and infiltration from precipitation. This was balanced through subsurface outflow to the Arabian Sea and evaporation from surface and subsurface.

Depth to groundwater varied from about 1.5 meters near the Indus River to more than 9 meters away from the river. The inflow/outflow from various river reaches during high and low flow conditions were confined to the riverine areas and did not contribute significantly to groundwater quality away from the river. Subsurface inflows from the upper areas and subsurface outflows to the Arabian Sea almost balanced each other (Hunting Technical Services 1965).

After the commissioning of Kotri Barrage and its canal system in 1955, the groundwater system started responding to a new source of recharge from the canal system and infiltration from an expanded cropping area. The gross command area (GCA) of Kotri Barrage is 1.308 million hectares, of which 1.126 million is cultivable command area (CCA). Since the commissioning of Kotri Barrage, average annual canal diversion in the area has been about 12.3 billion cubic meters (10.5 million acre-feet), of which nearly 6.2 billion cubic meters (5 million acre-feet) is recharged to groundwater as a result of seepage from the canal system and from irrigated areas. The water table started rising because of this additional recharge, and average depth of groundwater table recorded during June 1964 on both banks of the Indus River is shown here:

Left and right bank of Indus upstream of Kotri Barrage	Average depth to water table (m)
Right bank	3.5
Left bank	5.5
Average for both banks	5.0

Source: Basharat (MWH, ACE and NESPAK 2005).
Note: m = meters.

Average depth to water table as observed during June 1999 in the area irrigated by the four canals is shown here. The average depth on the left bank was 0.73 meters, whereas on the right bank, it was 0.84 meters.

Canal command	Average depth to water table (m)
Kalri Baghar Feeder	0.84
Lined Canal	0.51
Fuleli Canal	0.83
Pinyari Canal	0.77

Source: Basharat (MWH, ACE and NESPAK 2005).
Note: m = meters.

As a result of water table rise, a new equilibrium system was established with the sources of recharge and discharge shown here:

Source of recharge	Source of discharge
Recharge from canal system	Surface evaporation from ponded area
Subsurface inflow from upper area	Subsurface evaporation from shallow groundwater areas
Recharge from river system during high flow	Subsurface outflow to river during low flow and dry periods
Infiltration from cropped area	Subsurface outflow to deltaic area/sea

During the three drought years from 1999-2000 to 2002-03, there was a decline in water table in the area. The average depth of groundwater levels as evaluated from the field data was 4.01 meters in June 2002, and post-Kharif water tables had risen to 1.97 meters in October 2002.

Inflow-outflow studies carried out for the project area indicate that inflow and outflow components almost balance each other and do not significantly add to the groundwater reservoir. This implies that the canal system water that was created and is managed and accounted as a surface water system is now a surface water-groundwater system. This is important because resource risks are hard to notice or address if there is discrepancy between the physical resource and the manner in which it is accounted.

The most significant factor affecting groundwater fluctuations is subsurface evaporation from the shallow groundwater levels prevailing in the area. This evaporation may be contributing to the salinization of soils. The relationship developed for evaporation for the lower Indus region for various depths (Hunting Technical Services 1965) is given in figure A.1.

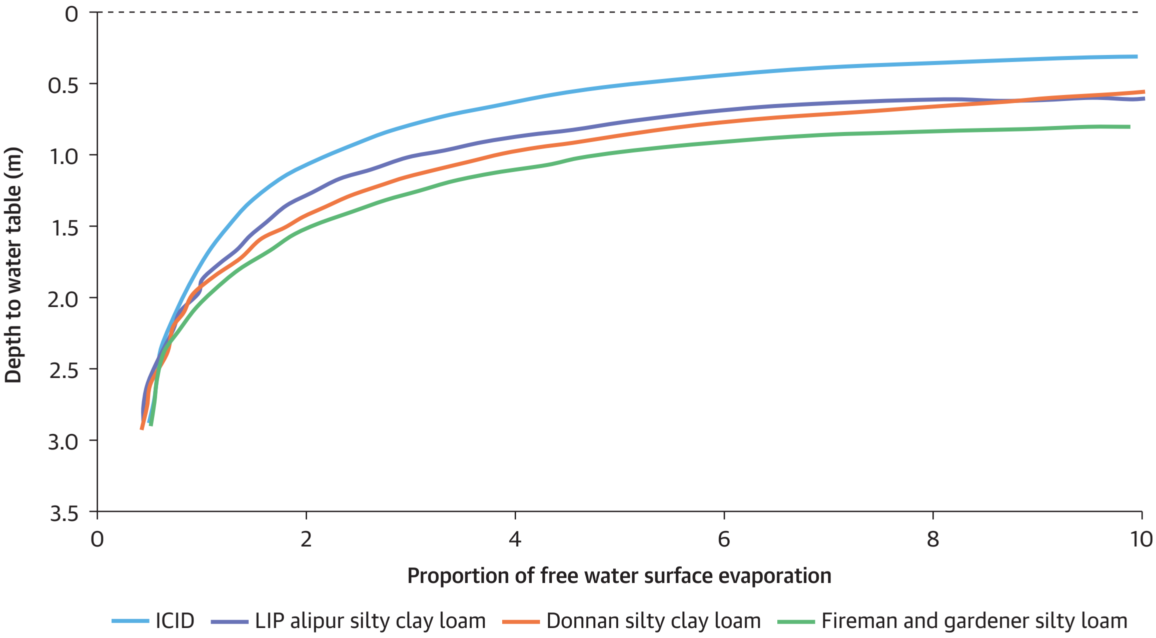
The net annual evaporation from the GCA of Kotri Barrage for various average depth ranges is shown here:

Annual Subsurface Evaporation as a Functon of Depth to Water Table

Average depth (m)	Annual subsurface evaporation (BCM)
1.52	3.82
1.22	5.74
0.91	8.29

Note: BCM = billion cubic meters; m = meters.

FIGURE A.1. Evaporation from Bare Soil with Water Table at Various Depths



Source: After Hunting Technical Services 1966.
Note: ICID = International Commission on Irrigation and Drainage; LIP = Lower Indus Project; m = meters.

The figures indicate that subsurface evaporation is the major component draining the areas with shallow water tables and may be contributing in the salinization of soils.

The specific yield of the aquifer was estimated to be 13 percent in the vicinity of Kotri Barrage to less than 10 percent in the lower areas near the Arabian Sea; the lower specific yield results in greater fluctuations in groundwater levels in response to recharge and discharge. Groundwater salinity determined by LIP consultants through 49 exploratory boreholes and 10 pumping tests from 1960 to 1965 gave the results tabulated here:

Average groundwater salinity with depth	Salinity (ppm)
Groundwater salinity up to 30.5 m (100 ft)	22,164
Groundwater salinity 30.5–61 m (100–200 ft)	29,870
Groundwater salinity 61–91.4 m (200–300 ft)	37,903
Groundwater salinity greater than 91.4 m (300 ft)	>35,000

Source: Hunting Technical Services 1966.
Note: ft = feet; m = meters; ppm = parts per million.

Left Bank Outfall Drain

The left bank of the Indus downstream from Sukkur Barrage is supplied with perennial water, which primarily supports a cotton crop in Kharif and wheat in Rabi. In 1932, when the barrage was constructed, the groundwater table was deep, so no provision for drainage was made. In 1959, just 26 years later, the problem of shallow water tables was widespread. Flooding after rainfall persists in these areas and causes considerable damage to cotton, as well as increases the incidence of malaria.

A drainage project was undertaken with World Bank assistance, and the study area was extended to cover the whole of Sindh under the LIP. The Left Bank Outfall Drain (LBOD) was first proposed in 1966 in a LIP report. The LBOD project planned to drain Nawabshah, Sanghar and Mirpurkhas districts, an area of 1.3 million acres on the left bank of the Indus in Sindh. The LBOD scheme planned to use a combination of surface and subsurface drainage and on-farm water management to improve productive agriculture by lowering the shallow saline water table. The design involved the use of deep tube wells, scavenger wells, buried interceptor drains, and tile drains, which discharge drainage effluent to surface drains and eventually to the sea via a spinal drain and tidal link canal. Despite technical assistance from the World Bank, many aspects of the scheme were poorly conceived. The operation and management of any scheme of this magnitude requires close monitoring and assessment, which was missing because of resource constraints and the lack of adequate institutional arrangements (Punthakey, Khowaja, and Prathapar 1997).

An increase in productivity because of an increase in cropping intensity, deeper water tables, and reduced salinity was expected in the LBOD area. WAPDA was monitoring water levels during pre- and post-monsoon, and a number of areas in Nawabshah district claimed to have increased crop yields. A groundwater modeling study of the LBOD scheme revealed significant deficiencies in monitoring data, such as pumping from existing tube wells, canal water levels, and irrigation and surface water usage. Where data are available, such as water levels, access is usually a difficult process. A much greater emphasis is needed on improved monitoring and archiving of all natural resource data, as well as accessibility for farmers and the wider community.

Deterioration of surface water bodies and groundwater from anthropogenic pollution is of much concern in Pakistan. A recent study in the LBOD system noted that sugar mills are discharging high levels of effluent directly into subdrains without any treatment. The study found 58 percent of samples taken from drains and handpumps have total dissolved solids and pH values beyond permissible limits and conclude that water from hand pumps is not fit for drinking (Mahessar et al. 2018). The authors recommend improved regulation and enforcement mechanisms be required to curtail these practices.

Subregional Groundwater Models in Sindh

The limited groundwater models developed for Sindh are mostly for CCAs. A few studies have focused on the Rohri Canal command area, there has been a study on Dadu Canal, as well as one in the LBOD-Nawabshah region. A subregional study undertaken by Basharat (MWH, ACE and NESPAK 2005) for assessing seawater intrusion downstream of Kotri Barrage is also reviewed. The remaining ones are either at the canal command level or focus on specific issues at a much smaller scale, such as modeling the impact of scavenger wells and skimming wells. The review provides an overview of the state of knowledge based on modeling studies in Sindh and provides insights for future studies that will need to be undertaken to support Sindh Water Policy[2] initiatives.

A regional modeling study is also being undertaken for the Left Bank Command of Sukkur Barrage in Khairpur, Naushahro Feroze, and Shaheed Benazirabad districts under an ACIAR project[3] on improving groundwater management. Results of this study are expected to be available in October 2020.

Groundwater Model for LBOD-Nawabshah

Ejaz (1998) developed a groundwater model for the LBOD-Nawabshah area and evaluated the present and future management of drainage tube wells in order to reduce waterlogging. The project area covers Naushahro Feroze, Nawabshah, and Sanghar districts of the Sukkur and Hyderabad divisions. The model was calibrated to observed conditions and predicted groundwater levels resulting from the operation of tube wells installed to drain waterlogged areas. The objective was to prepare a management plan for tube wells to maintain an adequate root zone environment for optimum cropping and yield. The model was used to improve understanding of changing from deep pumping wells to relatively shallow pumping wells. The model timeframe was from May 1988 to April 1998, covering pre- and post-LBOD Stage I project developments in the study area and the evaluation of predictions based on the continuation of the existing practices and implementation of proposed practices. The model compares the following scenarios.

Scenarios for Operation of LBOD in Sindh

Scenarios	Waterlogged area (ha)
April 1993: Identifying areas with water tables up to 1.5 m for surface drainage	210,800 (51%)
April 1998: Identifying areas with water tables within 1.5 m as a result of the operation of the LBOD draining at 526,958 m^3/d	102,800 (25%)
April 2010: Maintaining the operation of tube wells as in scenario 2 with LBOD operational until April 2010	98,000 (23.7%)
April 2010: All STWs operating at installed capacity with LBOD draining at 1,290,297 m^3/d	49,200 (12%)
April 2010: STWs operating at installed capacity in critical areas (water tables <1.5 m) with LBOD draining at 912,337 m^3/d	65,200 (16%)

Note: ha = hectare; LBOD = Left Bank Outfall Drain; m = meters; m^3/d = cubic meters per day; SCARP = Salinity Control and Land Reclamation Project; STW = SCARP tube well.

The LBOD-Nawabshah groundwater model identified areas with a water table within the critical limit of 1.5 meters. The model indicates that seepage from the main canals and distributaries, field application losses, and return flow from pumped groundwater is a significant inflow to the groundwater system. The simulated operation of tube wells at 41 percent of the installed capacity in the LBOD-Nawabshah component project area showed a significant reduction in the extent of waterlogged areas from 51 percent in April 1993 pre-tube well operation to 25 percent in April 1998. Continuing to operate tube wells at 41 percent of installed capacity was shown not to further significantly reduce the waterlogged area. The LBOD-Nawabshah model predicted that 24 percent of the area would remain waterlogged in April 2010, so in essence, it will maintain the status quo. However, the model predicted that operating the tube wells at their installed capacity would reduce the waterlogged area to 12 percent. The proposed management strategy of operating tube wells at their full capacity in areas with shallow water tables (less than 1.5 meters) limits the waterlogged area to 16 percent (see earlier scenarios). It would also reduce pumping of saline groundwater from 1.29 to 0.91 million cubic meters per day, resulting in a savings of about 30 percent when compared to the operation of all tube wells at full capacity. This is a promising direction; however, putting this strategy in place requires operation and maintenance of tube wells, as well as coordination and management at the institutional level.

What is evident from this modeling is that optimization of the groundwater system can provide important refinements to management strategies and avoid the costs incurred by blanket policies to increase tube well installation and groundwater use. This involves incorporation of various limitations and constraints of the hydrogeologic system and operation of tube wells while selecting the best management strategy for improved subsurface drainage. The government of Sindh needs to develop optimal strategies for drainage tube well operations in the LBOD-Nawabshah component project area to reduce risks from waterlogging and salinity, which results in losses in crop productivity. There are already some solar tube wells in operation in Sindh by larger private landholders for drainage as well as for irrigation supplies. Many of the existing diesel or electric drainage tube wells can also be converted to solar tube wells, which would save on electricity and diesel over the long term.

Groundwater Model for Second SCARP Transition North Rohri Project

Under this project (ACE et al. 1997), 382 SCARP tube wells (STWs) have been transitioned and replaced by 1,800 private tube wells (PTWs) and community tube wells (CTWs). This switch from deep pumping by STWs to relatively shallow pumping by PTWs and CTWs prompted the need to assess groundwater conditions under the changed scenario and its impact on groundwater levels and salinity.

The project area was composed of Moro (Naushahro Feroze district) and Sakrand (Shaheed Benazirabad district) units of SCARP North Rohri. Moro and Sakrand are situated on the left bank of Rohri, about 170 and 100 kilometers north of Hyderabad, respectively. The model simulated the groundwater flow system and solute transport in the aquifer under existing and future pumping conditions. The overall objective was to develop a sound basis for future management of groundwater resources in accordance with the safe yield of the aquifer(s).

The main objectives of the model included

- Simulation of interaction among various groundwater recharge, discharge, and quality parameters;
- Evaluation of impact of various pumping patterns/scenarios on future groundwater flow system and solute transport in the project area;
- Prediction of future changes in groundwater flow and quality;
- Development of decision support system for groundwater regulation; and
- Establishment of a base for similar applications in other SCARP projects in Sindh.

Hydrogeological studies were undertaken prior to model development. Seepage from Rohri Canal and its distribution system form the major source of recharge. Pumpage from tube wells and evapotranspiration from the shallow water table areas are the main source of groundwater discharge. The model area has been extended to the hydrologic boundaries in the east and west (that is, Rohri Canal and Indus River). The aquifer has been divided into three layers to represent pumping from comparatively shallow PTWs (layer 1) and deep STWs (layer 2).

The calibrated modeling period extended from April 1978 to March 1997, representing two stress periods per year composed of Kharif and Rabi seasons. The model simulated the future response of the aquifer under various pumping rates and the distribution of water quality until 2017. A solute transport model was developed utilizing data collected by previous investigations in the area and by the SCARP Monitoring Organization (SMO). Future scenarios explored the impact on the flow system of changes to the pumping pattern. The major stress on the aquifer will be in layer 1 as the deeper STWs will be non-operational and relatively shallow PTWs and CTWs will be operating in the future. This will affect the hydraulic equilibrium in the aquifer as STWs were mainly installed along the canals, generally at the head of watercourses (or directly pumped into the canal in case of saline STWs). PTWs and CTWs have generally been installed in the tail reaches of canals and watercourses where there is shortage of water and the quality of groundwater is relatively poor as compared to the head reaches.

The future scenarios considered in this study from 1997 to 2017 were:

- Scenario 1: The present rate of groundwater extraction for irrigation (0.332 billion cubic meters) continues in the future. Seepage wells and STWs are almost nonexistent, and the few operating STWs gradually close down. Groundwater is mainly pumped from layer 1 for irrigation and domestic use.

- Scenario 2: The present rate of abstraction continues, and seepage wells along Rohri Canal and STWs in shallow groundwater areas are rehabilitated or replaced. This will mean a total pumping of about 0.469 billion cubic meters (composed of 0.332 billion cubic meters from layer 1 and 0.136 billion cubic meters from layer 2).

- Scenario 3: Groundwater abstraction through PTWs and CTWs is increased to 0.411 billion cubic meters to meet water requirements at 130 to 140 percent cropping intensity without seepage wells and STWs.

- Scenario 4: Pumping from PTWs and CTWs as in scenario 3 with seepage wells and STWs rehabilitated or replaced.

The results of these scenarios showed the following:

- Scenario 1: Pumping at 0.332 billion cubic meters (0.269 million acre-feet) from layer 1 did not reduce groundwater levels and did not promote any significant change to the flow regime. Average salinity conditions at the start of the simulation for layers 1, 2, and 3 were 700, 850, and 10,000 parts per million, respectively. Solute concentrations in layer 1 increased to more than 2,000 milligrams per liter in Daulatpur, Mir Jono, and Sakrand areas as compared to initial conditions in 1997. In layer 2, solute concentrations showed a small increase in Sakrand area, and in layer 3 there was no impact on solute concentrations.

- Scenario 2: Layers 1 and 2 showed excessive depletion in the Sakrand area with the aquifer reaching equilibrium by 2007. Solute concentrations in layers 1 and 2 increased in the areas of Ahmed Bughio, Tharo Punher, and Sakrand, with no change for layer 3.

- Scenario 3: Model predictions indicated a drawdown of 0.61 to 0.91 meters (2 to 3 feet). Solute concentration remained largely unchanged, with results similar to scenario 1.

- Scenario 4: This scenario shows drawdowns are greater than in scenario 3. Solute concentrations in layers 1 and 2 showed a marked deterioration in groundwater quality in the southern regions, which was a result of deep pumping from layer 2. The authors recommended avoiding pumping from layer 2 as it resulted in declining water quality in layers 1 and 2. This is an important recommendation on how pumping from freshwater zones should be managed in Naushahro Feroze and Shaheed Benazirabad districts.

Assessment of Seawater Intrusion into the Aquifer below Kotri Barrage

The study area by Basharat (MWH, ACE and NESPAK 2005) covered the riverine area and the areas outside the embankments along the Indus River below Kotri Barrage, focusing on part of the Pinyari Canal command area on the left bank and a part of Kalri Baghar command area on the right bank. A model to assess seawater intrusion was developed by Basharat (MWH, ACE and NESPAK 2005), which covered an area at the downstream end of Keenjhar Lake (about 12 kilometers upstream of the town of Thatta) down to the mouth of the Indus River. The model extent was 115 kilometers long and 75 kilometers wide. Aquifer parameters for the model were obtained from the LIP reports. The model was designed with three layers, with the bottom elevation of the first layer at 50 meters below the mean sea level (MSL), the second layer at 100 meters below MSL, and the third layer at 150 meters below MSL.

The bed of Indus River is below MSL for between 130 and 160 kilometers upstream from the Arabian Sea. The depth varies from about 5 to 10 meters. This large deep channel varies in width from 0.4 to 1.5 kilometers and has a total volume of about 1.23 billion cubic meters. This deep channel always remains filled with either seawater or freshwater or a mixture of the two.

Basharat (MWH, ACE and NESPAK 2005) indicated the general direction of groundwater movement is from northeast to southwest. In some parts of the river, the groundwater aquifer contributes to the river, whereas in other parts, the river acts as a losing stream. Large volumes of groundwater flow through various creeks on the left bank to the Arabian Sea. However, on the right side of the river, the direction of flow is primarily from northeast to almost west, where the subsurface flow moves into large sea creeks. During the wet season, water tables rise by 1 to 2 meters or even more as a result of infiltration from rainfall, seepage from the canal system, percolation from cropped area, and recharge from some river reaches.

River water quality varied from about 250 milligrams per liter during high flow to 500 milligrams per liter under low flow conditions. The salinity of the Arabian Sea was measured at 32,000 to 33,000 parts per million during field investigations. The three sources of water—river, groundwater, and sea—have large variations in water quality, and this plays a major role in the importance of understanding their mixing and movement. The following hydrologic features were included in the model: Indus River, Kalri Baghar Feeder and its distribution channels, Pinyari Canal and its distribution channels, major drains, Haleji Lake, Hadero Dhand, coastal creeks, and tidal areas.

A key contribution of the work undertaken by Basharat (MWH, ACE and NESPAK 2005) was the data collected on riverbed conductivities. These represent valuable inputs for future modeling studies and the table here summarizes the results of permeability tests carried out in the Indus River bed at different places using the inverse auger-hole method.

In Situ Permeability Test for Indus River Bed

In situ permeability test at Indus River bed	Depth of hole from reference (cm)	k (m/d)
Danhdo (Sherazi Bander) on right bank	82.8	0.81769
Danhdo (Sherazi Bander) on left bank	90.0	0.35104
Dhandri on left bank	161.32	0.83686
Thatta-Sujawal Bridge on left bank	115.82	3.41208

Note: cm = centimeters; k = hydraulic conductivity; m/d = meters per day.

Groundwater elevation contours showed that it flows away from the major canals in the area on both sides of the river and the canal system in the area makes a major contribution to groundwater recharge. The seepage from canals is also being captured by the Indus River, starting from the upper regions of the model up to 10 kilometers upstream of Sherazi Bander. By contrast, the major part of seepage from the main and branch canals along the river goes to the Indus River because the water level there is lower than the surrounding aquifer groundwater level. A profile across the river near the city of Thatta shows the river water level is 2.9 meters ASL, whereas the minimum groundwater elevation in the aquifer along this section is 4.3 meters ASL, indicating river is gaining. The same situation was found for the cross-sectional profile near Chuhar Jamali. Here, too, the Indus River is gaining water from the aquifer and acting as a drain during a river discharge of 5,000 cubic feet per second. This shows that as long as the flows downstream of Kotri remain at low levels, the river will act as a drain, pulling groundwater toward the sea. The water balance tabulated here shows seawater intrusion is the major inflow, followed by irrigation return flows and river recharge. The dominant outflow is evapotranspiration and the sea boundary.

Groundwater Balance

Boundary condition	Inflows (MCM)	Outflows (MCM)
River (including canals, lakes)	1,112.9	129.9
Sea (boundary)	2,156.8	848.6
Boundary flows	9.8	2.2
Drains	0.0	219.8
Irrigation field losses	1,654.3	0.0
Tidal recharge to groundwater	1,269.3	0.0
Evapotranspiration	0.0	5,004.4
Total	**6,203.1**	**6,204.9**

Source: Adapted from Basharat (MWH, ACE and NESPAK 2005).
Note: MCM = million cubic metres.

There is also a small area where the river is gaining. This information and understanding of the relationship among the river, canals, and groundwater could be used to explore institutional structures that better account for groundwater and surface water interactions.

The main findings from the Basharat (MWH, ACE and NESPAK 2005) study is summarized here:

- There is low risk of seawater existing in the river below Thatta-Sujawal Bridge to contaminate the groundwater aquifer from Kotri Barrage to Dandari. The Indus River in this reach is acting as a drain during low river flows.
- Below Dandari, the interaction between the river flow and the groundwater is complex. The river flow could potentially recharge the aquifer dependent upon the seawater tides and the magnitude of river discharge.

In the canal command areas, the water table is sufficiently high and risk of seawater intrusion is low. The high-salinity groundwater is of ancient origin and is not contaminated by seawater intrusion. A study of water quality by Naseem and McArthur (2018) concluded that the chemistry of groundwater around Tando Allahyar (about 48 kilometers northeast of Hyderabad) rules out contributions to salinity from seawater or from brackish water of marine origin. The area of their study was above Kotri Barrage, and as seawater intrusion is significant below Kotri Barrage, there will be mixing with seawater. The model conclusions are based on a steady state model with constant river flow of 5,000 cubic feet per second downstream from Kotri Barrage and have to be viewed in light of the model limitations. Further work should include the use of a transient seawater intrusion model. Additionally, the study indicates the bed of the river is below sea level and that as long as there is low flow, the river acts as a drain. Under these conditions, high tidal incursions could transport seawater upstream to a considerable distance along the river channel. Scenarios should also be run in which the downstream flow is reduced to zero, as is the case during Rabi season.

Modeling Study of Waterlogging and Salinity in the Rohri and Khairpur Feeder East Canals

A modeling study by Chandio, Lee, and Mirjat (2012) was carried out in an area bounded between the Rohri and Khairpur Feeder East (KFE) canals over an area that covers 10,000 hectares. The main findings of the study indicated that the waterlogged area with a water table depth of less than 0.8 meters increased by 5.8 percent when the water level in the KFE Canal was increased by 0.6 meters with a pumping rate of 1,728 cubic meters per day. Similarly, when the water level in Rohri Canal was increased by 1 meter, the area under waterlogging increased by 10.5 percent. If water levels in both canals were increased simultaneously (0.6 meters in KFE and 1 meter in Rohri), the waterlogged area increased by 18.1 percent for the same well discharge. Thus, when surface water supplies are adequate, the canals operate at full supply level, which also contributes to increased seepage and waterlogging. Since this study, the Rohri Canal has been lined, and the effectiveness of the lining needs to be investigated as this should have led to a decrease in waterlogged area.

Chandio and Lee (2012) used a flow-and-transport model to predict the effects of different configurations of shallow skimming wells on the pumped water quality and on the development of saline groundwater upconing at the bottom of the well in the Rohri-KFE region. The salinity profile measured in test bores drilled to 35 meters showed the aquifer contains usable water with salinity that ranges between 600 and 1,200 milligrams per liter. Below 35 meters, the salinity was estimated from the LIP report, indicating salinity ranges between 1,568 and 3,000 milligrams per liter (Hunting Technical Services Ltd and Sir Mott MacDonald and Partners 1965).

The model results suggested that intermittent pumping through multistrainer wells could effectively be used to suppress saline water intrusion. However, these wells were found to induce saline water intrusion when the thickness of fresh-saline water interface was reduced to 4 meters. They further reported that the design and installation of skimming wells was not based on site-specific knowledge of aquifer lithology and the groundwater salinity profile but on meeting water requirement of farmers and on community experiences, with tube well design options provided by local drillers (Saeed and Ashraf 2005). The skimming wells vary between 18 and 30 meters deep. Field surveys of farmer-owned tube wells indicated well operation times vary from a few hours to 6 days and the well discharges vary between 1,296 and 2,592 cubic meters per day (15 and 30 liters per second). The stress on groundwater supplies is increased during irrigation canal closure time and during the crop sowing period.

Pumping Optimization Model for Dadu Canal Command

An optimization modeling study by Garg and Ali (2000) was undertaken for the Dadu Canal command area, which covers an irrigated area of 210,000 hectares. The alluvial sediments constitute an aerially extensive, fairly homogeneous, unconfined aquifer system with varying thickness from 30 to 60 meters, a mean hydraulic conductivity of 42 meters per day, and specific yield of 0.08. Seven hundred groundwater pumps are installed in the command, each with a capacity of 2,450 cubic meters per day. Wells are generally located at least 1 kilometer apart, and it was estimated there would not be any interference between wells. Thus, the optimization model for a single well indicated an optimal pumping rate of 1,200 cubic meters per day, and pumping rates provided for various pumping schedules. The main conclusion of the study was that despite the recommended optimal pumping rates, the lowest reaches of Dadu Canal command would be waterlogged. The authors suggested an increase in the tube well capacity of the command by 130 percent would allow an increase of 32 percent in cropping intensity and also reduce waterlogging and associated salinity impacts by 25 percent.

Conclusions

Although all numerical groundwater models are only as good as the data that support them, this problem is particularly acute for large models in highly complex environments in which information on future long-term changes to groundwater levels and quality are required. The Indus basin is one such environment. As Voss (2011) points out, model complexity and data requirements should be fitted to the groundwater environment and to the outcomes that are desired. The lack of good-quality, long-term groundwater data in Pakistan's Indus basin (see chapter 3) greatly complicates the task of numerical modeling and reduces the reliability of the results.

Notes

1. https://uaar.edu.pk/
2. Sindh Water Policy is being developed.
3. ACIAR is funding a project on improving groundwater management to enhance agriculture and farming livelihoods in Pakistan. The project is developing groundwater models at case study sites in Balochistan, Punjab, and Sindh.

References

ACE (Associated Consulting Engineers), NESPAK (National Engineering Services Pakistan), Zaheeruddin Consultants, and Harza Engineering Company.1997. *Second SCARP Transition North Rohri Pilot Project Completion Report, Annexure III: Hydrogeological and Mathematical Model Studies*. Karachi, Pakistan: Government of Sindh, Irrigation and Power Department.

Arshad, M, Ahmad, N, Usman, M. 2009. Simulating seepage from branch canal under crop, land and water relationships. International Journal of Agriculture and Biology 11 (5): 529-534 https://www.researchgate.net/publication/260791493_Simulating_Seepage_from_Branch_Canal_under_Crop_Land_and_Water_Relationships

Ashraf, A., and Z. Ahmad. 2008. "Regional Groundwater Flow Modelling of Upper Chaj Doab of Indus Basin, Pakistan Using Finite Element Model (Feflow) and Geoinformatics." *Geophysical Journal International* 173: 17-24. doi:10.1111/j.1365-246X.2007.03708.x.

Basharat, M. 2012. "Integration of Canal and Groundwater to Improve Cost and Quality Equity of Irrigation Water in a Canal Command." Doctoral dissertation, University of Engineering and Technology, Lahore, Pakistan. http://prr.hec.gov.pk/jspui/handle/123456789/468.

Basharat, M., and A.-U. Tariq. 2013. "Long-Term Groundwater Quality and Saline Intrusion Assessment in an Irrigated Environment: A Case Study of the Aquifer under the LBDC Irrigation System." *Irrigation and Drainage* 62: 510-23. doi:10.1002/ird.1738.

Chandio, A. S., T. S. Lee, and M. S. Mirjat. 2012. "The Extent of Waterlogging in the Lower Indus Basin (Pakistan)—A Modeling Study of Groundwater Levels." *Journal of Hydrology* 426: 103-11. https://www.sciencedirect.com/science/article/pii/S0022169412000601.

Chandio, A.S., and Lee, T.S. 2012. Managing Saline Water Intrusion in the Lower Indus Basin Aquifer. *Water Resources Management* 26, 1555-1576. https://doi.org/10.1007/s11269-011-9972-1

Ejaz, M.S. 1998. Waterlogging and Salinity in the Sindh Province Pakistan, Vol I supplement 1.c. Drainage in the LBOD Project Operational Concerns and Quality of Pumped Effluent. Pakistan National Drainage Program, International Irrigation Management Institute, Lahore Pakistan.

Garg, N. K., and A. Ali. 2000. "Groundwater Management for Lower Indus Basin." *Agricultural Water Management* 42: 273-90. https://www.sciencedirect.com/science/article/pii/S0378377499000438.

Government of Pakistan. 2012. *Agricultural Statistics of Pakistan*. Statistics Division, Government of Pakistan, Islamabad.

Hunting Technical Services Ltd and Sir Mott MacDonald and Partners. 1965. *Lower Indus Report, Physical Resources-Groundwater, Volume 6, Supplement 6.1.3, 4 and 5*. West Pakistan Water and Power Development Authority.

——. 1966. *Lower Indus Report, Part One, Present Situation*. West Pakistan Water and Power Development Authority.

Khan, A. D., N. Iqbal, M. Ashraf, and A. A. Sheikh. 2016. *Groundwater Investigations and Mapping in the Upper Indus Plain*. Islamabad: Pakistan Council of Water Resources Research.

Khan, H.F, Ethan Yang Y.C., Ringler, C., Wi, S., Cheema, M.J.M., and Basharat, M. 2016. Guiding Groundwater Policy in the Indus Basin of Pakistan Using a Physically Based Groundwater Model. Journal of Water Resources Planning and Management: 143 (3).

Khan, S., T. Rana, K. Ullah, E. Christen, and M. Nafees. 2003. "Investigating Conjunctive Water Management Options Using a Dynamic Surface-Groundwater Modelling Approach: A Case Study of Rechna Doab." Technical Report 35/03, CSIRO Land and Water. Canberra. https://publications.csiro.au/rpr/download?pid=procite:984d387c-8d77-4c0b-b955-71b2602948e6&dsid=DS1

Lahmeyer International and National Development Consultants. 2013. *Groundwater Monitoring, Modelling and Management for LBDCIP*. Pakistan: Government of Punjab Irrigation and Power Department Lahore.

Mahessar, A. A., A. L. Qureshi, A. N. Laghari, S. Qureshi, S. F. Shah, and F. A. Shaikh. 2018. "Impact of Hairdin, Miro Khan and Shahdad Kot Drainage on Hamal Dhand, Sindh." *Engineering, Technology and Applied Science Research* 8 (6): 3652-56.

MWH (Montgomery Watson Harza), ACE (Associated Consulting Engineers) and NESPAK (National Engineering Services Pakistan). 2005. "Study on Water Escapages Below Kotri Barrage to Check Seawater Intrusion (Study-I). Final Report, Volume I." Government of Pakistan, Ministry of Water and Power, Federal Flood Commission. https://www.academia.edu/27505797/Study_on_Water_Escapages_below_Kotri_Barrage_to_Check_Sea_Water_Intrusion_Study-I

Naseem, S., and J. M. McArthur. 2018. "Arsenic and Other Water-Quality Issues Affecting Groundwater, Indus Alluvial Plain, Pakistan." *Hydrological Processes* 32 (9): 1235–53. https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.11489.

PPSGDP (Punjab Private Sector Groundwater Development Project). 2000. "Groundwater Management and Regulation in Punjab." Draft Technical Report No. 45, prepared by Groundwater Modelling Team of Punjab Private Sector Groundwater Development Project, Project Management Unit, Irrigation and Power Department, Government of Punjab, Pakistan.

Punthakey, J. F., M. R. Khan, M. Riaz, M. Javed, G. Zakir, M. Usman, M. Amin, R. N. Ahmad, J. Blackwell, R. Culas, I. A. Baig, and E. Christen. 2015. *Optimising Canal and Groundwater Management to Assist Water User Associations in Maximizing Crop Production and Managing Salinisation in Pakistan: Assessment of Groundwater Resources for Rechna Doab, Pakistan.* Report to Australian Center for International Agricultural Research (ACIAR), Ecoseal - Water Resources Management.

Punthakey, J. F., A. A. Khowaja, and S. A. Prathapar. 1997. *Health and Irrigation Management in Sindh - Issues and Research Priorities.* Consulting Report for International Irrigation Management Institute, Pakistan.

Saeed, M. M., and Ashraf, M. 2005. Feasible design and operational guidelines for skimming wells in the Indus Basin, Pakistan. Agricultural Water Management, 74:1-24.

Sarwar, A., Eggers, H. 2006. Development of a conjunctive use model to evaluate alternative management options for surface and groundwater resources. Hydrogeology Journal 14: 1676–1687. https://doi.org/10.1007/s10040-006-0066-8

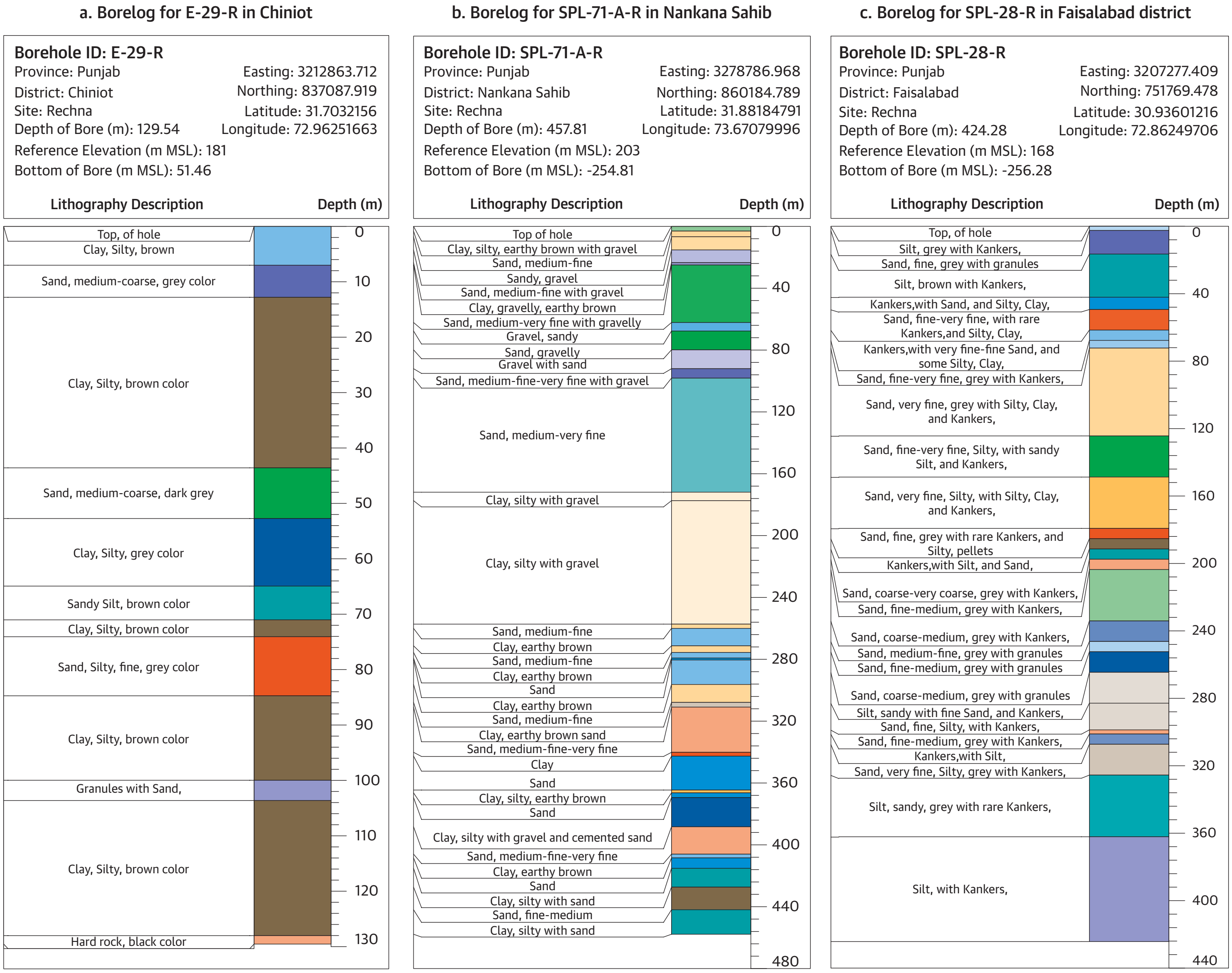
Shakoor, A., M. Arshad, R. Ahmad, Z. M. M. Khan, U. Qamar, H. U. Farid, M. Sultan, and F. Ahmad. 2018. "Development of Groundwater Flow Model (MODFLOW) to Simulate the Escalating Groundwater Pumping in the Punjab, Pakistan." *Pakistan Journal of Agricultural Sciences* 55 (3): 635–44. https://www.researchgate.net/profile/Muhammad_Sultan8/publication/326304638_Development_of_groundwater_flow_model_Modflow_to_simulate_the_escalating_groundwater_pumping_in_the_Punjab_Pakistan/links/5b50897345851507a7af337d/Development-of-groundwater-flow-model-Modflow-to-simulate-the-escalating-groundwater-pumping-in-the-Punjab-Pakistan.pdf.

Voss, C. I. 2011. "Editor's Message: Groundwater Modeling Fantasies - Part 1, Adrift in the Details." *Hydrogeology Journal* 19: 1281–84.

Yang, YCE., Brown, CM., Yu, WH., and Savitsky, A. 2013. An introduction to IBMR—A hydro-economic model for the climate change impact assessment in the Indus River in Pakistan. Water Int., 38(5), 632–650

Appendix B
Selected Borelogs in the Indus Basin

FIGURE B.1. Selected Borelogs in Rechna Doab, Punjab



a. Borelog for E-29-R in Chiniot

Borehole ID: E-29-R
Province: Punjab
Easting: 3212863.712
District: Chiniot
Northing: 837087.919
Site: Rechna
Latitude: 31.7032156
Depth of Bore (m): 129.54
Longitude: 72.96251663
Reference Elevation (m MSL): 181
Bottom of Bore (m MSL): 51.46

b. Borelog for SPL-71-A-R in Nankana Sahib

Borehole ID: SPL-71-A-R
Province: Punjab
Easting: 3278786.968
District: Nankana Sahib
Northing: 860184.789
Site: Rechna
Latitude: 31.88184791
Depth of Bore (m): 457.81
Longitude: 73.67079996
Reference Elevation (m MSL): 203
Bottom of Bore (m MSL): -254.81

c. Borelog for SPL-28-R in Faisalabad district

Borehole ID: SPL-28-R
Province: Punjab
Easting: 3207277.409
District: Faisalabad
Northing: 751769.478
Site: Rechna
Latitude: 30.93601216
Depth of Bore (m): 424.28
Longitude: 72.86249706
Reference Elevation (m MSL): 168
Bottom of Bore (m MSL): -256.28

Data Source: After CSIRO. 2017. Database of Lithology Borelog Data of the Indus Basin, Pakistan. Sustainable Development Investment Portfolio (SDIP) Project. CSIRO, Australia.

Appendix C
National Five-Year Plans and Institutional Roles for Groundwater

TABLE C.1. An Overview of National Five-Year Plans for Groundwater Management

Five-year plan	Period	Main water-related focused areas	Remarks
First	1955–60	• Increased agricultural production through expansion of irrigated agriculture and control of waterlogging and salinity • Cheap electricity to accelerate agricultural and industrial development	Main focus was on surface water; groundwater was viewed through waterlogging and salinity
Second	1960–65	• Increased agricultural production through expansion of irrigated agriculture and control of waterlogging and salinity • Cheap electricity to accelerate agricultural and industrial development	Indus Water Treaty of 1960 opened new ways of interriver water transfer. The plan was successful as it completed the following projects: • Guddu Barrage, 1962 • Sidhnai and Mailsi barrages, 1965 • Mangla Dam and allied works • Warsak Dam
Third	1965–70	• Implementation of measures for waterlogging and salinity continued • Water conservation • Use of groundwater to supplement canal irrigation	• Construction of Mangala reservoir, 1961–65 • Construction of Qadirabad Barrage, 1967 • Completion of Marala and Rasul barrages, 1968
Fourth	1970–75	• Implementation of measures for waterlogging and salinity continued • Water conservation • Use of groundwater to supplement canal irrigation	• Although this period was called under the fourth five-year plan, factually no five-year plan was prepared—annual allocations replaced the five-year plan • Tarbela reservoir was completed, 1968–76
Fifth	1978–83	• Main focus was on the water management and reduction of conveyance losses • The plan also ensured involvement of water users in the improvement of watercourses	The fifth and sixth five-year plans share the key activities of involving farmers in the water management through water user groups
Sixth	1983–88	• The plan focused on improved water management and participation of farmers • OFWM was also initiated	Improvement of water courses continued
Seventh	1988–93	• Water saving through water management techniques and participatory improvement in irrigation schemes were introduced • Planning of water resources projects continued	Laser land levelling was introduced, which is claimed to be an effective water saving techniques. However, authenticated and evidenced-based proof was needed.

table continue next page

TABLE C.1. continued

Five-year plan	Period	Main water-related focused areas	Remarks
Eighth	1993–98	It included • Formation of farmer's organizations; and • Decentralization of the water management system through area water boards	Provincial irrigation departments were the main focus
Ninth	1998–2003	The ninth five-year plan was not released; in 2001, the government approved a 10-year perspective (2001–11)	National drainage program was implemented throughout the country; provincial drainage authorities were formed
Tenth	2010–15	Not implemented	none
Eleventh	2013–18	Prioritized: • Construction of water storages • Water conservation • Flood management • IWRM • Improving water governance • Control water pollution • Transboundary issue • Water infrastructure financing • Sustainable use of land and water resources in agriculture (aquifer recharge in arid and semiarid regions) • Improving water use efficiency	Following the Eighteenth Amendment, the federal government's plans mainly cover the interprovincial coordination, capacity building, development, and management of large dams and reservoir flood management in the main rivers and interprovincial water courses. The water use management, provincial drainage, development of small dams and reservoir, and management of water quality is mainly the responsibility of the provincial governments and is part of provincial development plans.
Twelfth	(2020–25)	The plan is in draft and broadly covers: • Sustained growth • Climate change challenges • Clean energy • Agricultural productivity • Infrastructure development and industrial revival • Progress on Sustainable Development Goals of the United Nations	The provinces continue to work through the annual development plan and their planning strategy is evolving. For example, Punjab growth strategy 2018 is expected to guide the investments in improving the productivity of agriculture and livestock with a main focus on • Improved quality of research; • Climate change adaptation; and • Better on-farm water management

Notes: IWRM = integrated water resource management; OFWM = on-farm water management;

TABLE C.2. **Roles and Responsibilities of Groundwater-Related Institutions**

Number	Institutions	Constitution and composition	Mandate	Groundwater-related activities
	Federal government institutions			
1	Council of Common Interests (CCI), Federal Ministry of Interprovincial Coordination, Islamabad http://www.ipc.gov.pk/	The CCI was first constituted under the Rules of Business 1973. Its secretariat is in the Federal Ministry for Interprovincial Coordination. The president reconstituted the CCI on August 31, 2018, with the prime minister as chair and four provincial chief ministers and federal ministers of finance, interprovincial coordination, and industry as the members.	The CCI is responsible to formulate and regulate policies in relation to the matters enumerated in part II of the federal legislative list (annex I) and exercise supervision and control over related matters. It undertakes resolution of a dispute among the federation and the federating units or area governments regarding their rights on water from any natural source. The decisions are made by majority members and are appealable.	• The CCI is a forum to resolve issues on provincial shares and conflicts among the provinces. It ensures equitable distribution of water among the provinces and formulates and regulates policies. • The CCI approved the Water Apportionment Accord and agreement among the provinces on share of Indus water. However, the CCI has not been involved directly in groundwater-related matters. • As groundwater is closely linked to surface water, any change in share in surface water can affect the groundwater.
2	Ministry of Water Resources (MoWR), Government of Pakistan, Islamabad http://www.mowr.gov.pk	The MoWR was constituted on August 4, 2017, after dissolving Ministry of Water and Power. Its subordinating organizations are WAPDA (water wing), Federal Flood Commission (FFC), Indus River System Authority, and Pakistan Commissioner for Indus Water (PCIW).	Under Rule of Business 1973 and Cabinet Division's notification vide SRO-921 (i), dated September 13, 2017, schedule 1 of Rule of Business (item 40), the MoWR is responsible for • Development of water resources; • Indus Water Treaty of 1960 and Indus Basin Works; and • Administrative control of a tube well construction company.	The MoWR is responsible for implementation of the National Water Policy, resolving transboundary water issues, conducting federal-level water resource investment planning, and approval of water projects.

table continue next page

TABLE C.2. continued

Number	Institutions	Constitution and composition	Mandate	Groundwater-related activities
2.1	Water and Power Development Authority (WAPDA) *www.wapda.gov.pk/*	Since October 2007, WAPDA was divided into WAPDA and Pakistan Electric Power Company. WAPDA is responsible for water and hydropower development and is based in Lahore but acts through its three regional offices in Hyderabad, Lahore, and Peshawar. It is constituted on the chairman and three members and has a central planning department.	WAPDA was constituted in 1958 under Parliamentary Act 1958 and amended as Notification No. Leg. 3 (13), dated March 37, 1959, as a semiautonomous authority for development of water (irrigation, drainage, water supply, flood control, recreational water use, inland navigation) and power sectors.	WAPDA works under the MoWR and develops and manages surface water and groundwater resources at the national level.
2.1.1	International Waterlogging and Salinity Research Institute (IWASRI), WAPDA	IWASRI works under WAPDA. Its head office is in Lahore. IWASRI coordinates and manages allied organizations, namely the Mona Reclamation Experimental Project, Bhalwal; Lower Indus Water Management and Reclamation Research Project, Hyderabad; International Sedimentation Research Institute, Pakistan; and SMO, Lahore.	IWASRI was established in 1986 as a research institute to conduct research on waterlogging and salinity, groundwater, surface water, and environment issues by developing economically feasible solutions.	• IWASRI conducts research and monitoring of groundwater, waterlogging, and salinity. • After the Eighteenth Amendment, a reduction in funds affected IWASRI's work significantly.
2.1.2	SCARP Monitoring Organization (SMO), WAPDA	SMO was created for monitoring and data acquisition. Implemented for Punjab by SMO-I at Lahore, and for Sindh by SMO-II at Hyderabad.	Monitoring of waterlogging, salinity, and groundwater	• A parallel organization (MONA) was created for field experimentation. Both SMO and MONA worked under GM planning in WAPDA but with independent Chiefs. In later years of operation, SMO was attached to IWASRI.

table continue next page

TABLE C.2. continued

Number	Institutions	Constitution and composition	Mandate	Groundwater-related activities
3	Ministry of Planning, Development and Reform (MPDR), Planning Commission (PC), Islamabad https://www.pc.gov.pk	The PC works under the MPDR and is an important body that reviews and approves development projects.	Since 1952, the PC acts as a financial and public policy development institution of the government of Pakistan. It undertakes research studies and state policy development initiatives. It was responsible for developing five-year plans and PSDPs.	• The PC prepares, reviews, and approves water resources related to planning, policy, and project documents for federal and provincial governments. • The PC has a major influence and role in formulating five-year plans and PSDPs covering groundwater.
4	Ministry of National Food Security and Research (MNFSR) http://www.mnfsr.gov.pk/	The MNFSR is composed of animal, crop, and food security commissioners, federal water management cell, and PARC.	The MNFSR is mainly responsible for policy formulation, economic coordination, and planning with respect to food grain and agriculture and implementation of food security policy.	• Food security policy requires sustainable use of existing water resources when groundwater plays a critical role in agricultural productivity. • Groundwater is an integral part of management planning and research for the agricultural production system.
4.1	Pakistan Agriculture Research Council (PARC) and National Agriculture Research Center	PARC works under the MNSFR for capacity building and research on water, agriculture, social, environment, and climate change impacts.	PARC was established in 1981 to • Undertake and coordinate on agricultural research; • Disseminate research results; • Arrange training; and • Manage a research library.	• The council conducts research on surface water and groundwater and climate change. • It advises and disseminates results of studies on groundwater use in agriculture. • It provides training on efficient use of water in agriculture.
4.2	Federal Water Management Cell, Islamabad	The cell works under the MNSFR and coordinates with the provinces for agricultural water management and investment planning.	The Federal Water Management Cell was established in 1979 to assist the MNFSR on agriculture mechanization policy and strategy, water conservation, and efficient use in agriculture; develop a database; and raise awareness.	The cell assists the MNSFR to formulate legislative and regulatory frameworks for sustainable management of groundwater resources.

table continue next page

TABLE C.2. continued

Number	Institutions	Constitution and composition	Mandate	Groundwater-related activities
5	**Ministry of Science and Technology, Government of Pakistan, Islamabad, through the following agencies.**			
5.1	Pakistan Council of Research in Water Resources (PCRWR), Islamabad http://www.pcrwr.gov.pk/	The PCRWR was established in 1964 and converted into a corporate body through the Pakistan Council of Research in Water Resources Act 2007. The PCRWR works under the Ministry of Science and Technology and has established its regional offices in the provinces for effective coordination and support.	The PCRWR is mandated to conduct, organize, coordinate, and promote research in all fields of water resources engineering, planning, and management so as to optimally use the available land and water resources and to help achieve sustainability in the agricultural sector.	• The PCRWR advises on water policy advice, research, coordination, investment planning, and capacity building. • It works on groundwater quantity and quality assessment, groundwater recharge, and safe use of drinking water supply.
6	Ministry of Climate Change, Government of Pakistan, Islamabad http://mocc.gov.pk/; http://www.environment.gov.pk/	The ministry encompasses the Pakistan Environment Protection Agency and Global Climate Impact Study Center (GCISC).	The Environment Protection Agency was under section 5 of the Pakistan Environmental Protection Act (PEPA) 1997 to • Enforce PEPA 1997; • Approve Environmental Impact Assessments (EIA) and Initial Environmental Examinations (IEE). • Issue certificates for environment labs in the Islamabad; • Establish national environmental quality standards; • Identify needs for legislation in environment and water; and • Publicize environment related information.	• The Environment Protection Agency influences groundwater management through pollution control, contamination management, and protection of groundwater quality. • It helps with coordination, investment planning, and donor coordination relevant to water pollution control issues.

table continue next page

TABLE C.2. continued

Number	Institutions	Constitution and composition	Mandate	Groundwater-related activities
6.1	Global Change Impact Studies Center (GCISC) http://www.gcisc.org.pk/	Under the Ministry of Climate Change, the GCISC conducts research on climate change, including water resources.	The center was established in May 2002 and granted status of a regular national entity in 2013 through GCISC Act 2013. Its mandate is for research, capacity building, policy analysis, information dissemination, and assistance to national planners and policy makers on issues related to past and projected future climatic changes in the country.	The center studies the likely effects of climate change on the key socioeconomic sectors of the country, such as water, food, agriculture, energy, forestry, health, and ecology, as well as appropriate adaptation and mitigation measures.
	Khyber Pakhtunkhwa province			
7	Planning and Development Department, Government of Khyber Pakhtunkhwa, Peshawar	The Planning department has its wing for water, agriculture and environment to address the relevant issues with those provincial departments.	Planning, coordinating, and approving all water-related policy, planning, and project documents.	• Planning and Development plays a coordinating and decision-making role at the provincial level on groundwater management. • It can influence groundwater management through project provisions and approval relevant to groundwater management.
8	Irrigation and Power Department, Government of Khyber Pakhtunkhwa, Peshawar	Works through field offices at the canal command level.	Planning, research, development, and management of irrigation water conveyance system, flood, drainage, groundwater, and land reclamation.	Main provincial department that deals with water for development and resource management for irrigation uses.
9	Agriculture Department, Government of Khyber Pakhtunkhwa, Peshawar	Works through directorate of OFWM.	Planning, development, management, and coordination of all on-farm-level waters for conservation and productivity enhancement.	The only government department that works at the farm level and can influence irrigation uses of groundwater.

table continue next page

TABLE C.2. continued

Number	Institutions	Constitution and composition	Mandate	Groundwater-related activities
10	Public Health Engineering Department (PHED)	PHED was constituted to administer water supply and sanitation. Later on Water and Sanitation Agencies (WASA's) were created to manage the water supply and sanitation in big cities.	Plan, develop, and manage domestic water supplies of acceptable quality; set tariffs; and collect revenue from domestic water customers.	The PHED and WASAs provide domestic water supply, impose tariffs, and collect revenue. Thus, they can influence groundwater management through regulation, pricing, and reduction in nonrevenue water, such as a ban on home-based car washing.
	Punjab province			
11	Planning and Development Department Government of Punjab, Lahore	Planning and Development members for water, agriculture, and environment.	Planning, coordinating, and approving all water-related policy, planning, and projects documents.	Through approval of Planning Commission Proforma (PC-1), the Planning and Development department can influence decisions on groundwater development and protection at the provincial level.
12	Punjab Irrigation Department (PID), Government of Punjab, Lahore • Punjab Irrigation and Drainage Authority (PIDA)—abolished in June 2019	The PID works through the DLR and other field offices at canal command levels. • PIDA was created to manage all the irrigation water through water user associations, farmers organizations, and area water boards (since dissolved).	Planning, development, and management of canal water conveyance system, flood, drainage, and land reclamation.	The DLR monitors groundwater at selected locations (Jhang, Khanewal, Multan, Okara, and Sahiwal districts) but has no role in groundwater control in the field.
13	Agriculture Department, Government of Punjab, Lahore	Works through its OFWM directorate in Lahore.	Planning, development, management, and coordination of all on-farm-level waters for conservation and productivity enhancement.	• OFWM is involved in water course lining, therefore conserving the pumped water and reducing the pumping requirement. • The agriculture department has set laboratories at the district level to test groundwater quality for agriculture and advise farmers accordingly. However, it does not undertake the responsibility of licensing, control of tube well installation, or aquifer management.

table continue next page

TABLE C.2. continued

Number	Institutions	Constitution and composition	Mandate	Groundwater-related activities
14	Public Health Engineering Department (PHED)	WASA, PHED, and local governments	Plan, develop, and manage domestic water supplies of acceptable quality, set tariffs, and collect revenue from domestic water customers.	It is involved in groundwater management through demand management, tariff control, and reduced nonrevenue water.
15	Punjab Environment Protection Department http://epd.punjab.gov.pk/	Environment Protection Agency	Mainly concern for water quality and water-based ecosystem services.	The EPA is under-resourced to take over its responsibilities fully.
16	University of Engineering and Technology, Lahore	Through its departments and Center of Excellence in Water Resource Engineering.	A higher degree-awarding institute in water resources also involved in capacity building.	Offers trainings and guidance on groundwater through participation in meetings.
	Sindh province			
17	Planning and Development Department, Government of Sindh, Karachi	Department has Planning and Development members for each of water, agriculture, and environment.	Planning, coordinating, and approving all water-related policy, planning, and project documents.	All major decisions on groundwater at the provincial level need concurrence by the Planning and Development department.
18	Irrigation Department, Government of Sindh, Karachi • Sindh Irrigation and Drainage Authority (SIDA), Hyderabad	Planning, development, and management of irrigation conveyance system, flood, drainage, and land reclamation. • SIDA manages a few irrigation canals through water user associations, farmers organizations, and area water boards.	Managing irrigation, drainage and small dams.	Low or no role in groundwater extraction and uses. • SIDA, through farmers organizations, has a role in groundwater management.
19	Agriculture Department, Government of Sindh, Karachi, through its OFWM directorate	Planning, development, management, and coordination of all on-farm-level waters for conservation and productivity enhancement.	On-farm water management.	Practically, little role in groundwater management except for improvement of water courses from tube wells locations to the field.
20	Public Health Engineering Department (PHED)	Plan, develop, and manage domestic water supplies.	Plan, develop, and manage domestic water supplies of acceptable quality, set tariffs, and collect revenue from domestic water customers.	Can manage groundwater through pricing, reduced nonrevenue water, and regulation.

table continue next page

TABLE C.2. continued

Number	Institutions	Constitution and composition	Mandate	Groundwater-related activities
21	Environment, Climate Change and Coastal Development Department, Government of Sindh, Karachi	Main concern is water quality and water-based ecosystems services.	To implement environment related protocols in provinces including groundwater quality	The department is backed by an act, but it has a low capacity to manage large-scale issues of groundwater quality contamination and pollution.
22	Mehran University of Engineering and Technology, Jamshoro, Sindh: USA-PAK Centre for Advanced Studies in Water Resources	A higher degree-awarding institute in water resources also involved in capacity building.	MUET is a leading Engineering, research and teaching university of Pakistan.	Offers trainings and guidance on groundwater through participation in meetings.
	Nongovernmental organizations			
23	World Wide Fund (WWF) for Nature, Islamabad and Lahore	An international NGO having interest in nature-based water management.	Non-profit organization promoting water and environment related good practice. Works towards sustaining the natural world for the benefit of people and nature.	Seeks to influence the government and civil society through advocacy on groundwater management—for example, actions under Alliance for Water Stewardship in Pakistan and Groundwater Working Group for Citywide Partnership.
24	International Union for Conservation of Nature (IUCN)	An international NGO having interest in nature-based water management.	IUCN is a network driving change for sustainability. Mainly involved in water related activities in Pakistan.	Seeks to influence the government and civil society through advocacy on groundwater management. Water governance initiative in FATA area, promoting integrated coastal management, and community-based control of seawater intrusion in delta area are examples.
25	National Rural Support Program (NRSP), Islamabad http://www.nrsp.org.pk/	An NGO for social mobilization and social water aspects.	The NRSP was established in 1991 under section 42 of Companies Ordinance 1984 to alleviate poverty by harnessing people's potential and undertaking development activities in Pakistan.	Work with communities and end users through awareness raising, social mobilization, and community development.

Note: CCI = Council of Common Interests; DLR = Directorate of Land Reclamation; FATA = Federally Administrated Tribal Area ; GCISC = Global Change Impact Studies Center; IUCN = International Union for Conservation of Nature; IWASRI = International Water Logging and Salinity Research Institute; MNFSR = Ministry of National Food Security and Research; MoWR = Ministry of Water Resources; MPDR = Ministry of Planning, Development and Reform; NGO = nongovernmental organization; NRSP = National Rural Support Program; OFWM = on-farm water management; PARC = Pakistan Agricultural Research Council; PC = Planning Commission; PCRWR = Pakistan Council of Research in Water Resources; PEPA = Pakistan Environmental Protection Act; PHED = Public Health Engineering Department; PID = Punjab Irrigation Department; PIDA = Punjab Irrigation and Drainage Authority; PSDP = public sector development program; SCARP = Salinity Control and Land Reclamation Project; SIDA = Sindh Irrigation and Drainage Authority; SMO = SCARP Monitoring Organization; WAPDA = Water and Power Development Authority; WASA = Water and Sanitation Agency; WWF = World Wide Fund.

Appendix D
Implementing Recommendations

TABLE D.1. Supporting Priorities, Strategic Actions, Outcomes, and Suggested Performance Measures for Sustainable Groundwater Management

Supporting priorities	Key strategic actions	Required resources	Outcomes	Performance measures
Resource information	**Technical reform** • On management area basis, create a register of existing monitoring assets and equipment (across all agencies) • Prepare protocols and quality assurance/quality control (QA/QC) procedures for data collection activities • Prepare staffing and equipment schedules for routine monitoring • Enhance monitoring network for strategic planning to provide robust spatial data for groundwater assessment, planning, and management (quantity, quality, uses, and users) • Create system for a unique ID (geotagged) for every bore, tube well, well, and piezometer (public or private) in the Indus basin • Create a lasting database for static and dynamic groundwater data • Measure temporally robust groundwater levels, EC, and depth EC profiles **Policy reform** • Develop robust information management systems, data archiving, and transparent access arrangements • Introduce the requirement to register all bores/tube wells within a management area • Ensure common data standards, nomenclature, and infrastructure IDs among agencies and jurisdictions **Institutional reform** • Identify institutional responsibility and an institutional home for the collection, curation, and sharing of groundwater data (level, quality, and use) • Create coordination mechanisms among agencies and with stakeholders • Budget (CAPEX) for the maintenance and replacement of monitoring infrastructure (bores), equipment (measuring devices, vehicles), and disposables (batteries, EC meter calibration liquids) • Budget (OPEX) for the requisite amount of staff time, field allowances, and training to deliver the required monitoring • Appoint technically and financially competent team leaders who are accountable for scheduling, monitoring, and data management • Build capacity in monitoring groundwater resources across all stakeholders	• Human resources to conduct monitoring and data management tasks on a permanent basis • Financial resources for CAPEX and OPEX components of the monitoring tasks • Contribution from all sectors and tiers of government with an interest or role in groundwater use or management • Accountable agency to provide an institutional home for groundwater data	Purposely developed website to house data permanently and provide access to all users of the following: • Published protocols for data collection • Up-to-date and historic groundwater-level data • Up-to-date and historic groundwater quality data • Current and historic groundwater assessment reports • Improved transparency and access to water information	• An asset management plan • Evidence of coordination among government agencies • Evidence of representative stakeholder involvement • Record of staff numbers and budget expenditure assigned • Annual number of groundwater reports • Number of students, researchers, users, and practitioners benefitted through web-based data availability

table continues next page

TABLE D.1. continued

Supporting priorities	Key strategic actions	Required resources	Outcomes	Performance measures
Water resources and basin planning	**Technical reform** • Conduct a prioritization assessment for monitoring and management of groundwater at community and canal command scales • Delineate integrated water planning and management areas (for example, CCA) and identify all water resource assets within the boundaries of those areas • Use monitoring data to map spatial and temporal trends (level and quality) in all water resources to analyze their status and interaction • Delineate areas of groundwater depletion, waterlogging, salinity, and those affected by specific contaminants (hotspots) • Identify water budgets (see also groundwater management priority area) • Develop groundwater availability and use scenarios at different spatial scales under changing conditions • Confirm local processes of saltwater ingress into groundwater • Identify pollution sources and define strategies to protect groundwater quality • Identify ecosystem services that are required for improving water quality of lakes, wetlands, and the Indus delta **Policy reform** • Mandate the development of plans for water resource management areas and an exclusive plan for coastal regions • Support the collection of national data sets to assist water resource planning • Ensure the coordination of water resource planning across jurisdictional boundaries • Ensure the coordination across sectors and among tiers of government **Institutional reform** • Assign institutional responsibility for developing water plans • Strengthen provincial government capacity to draft and implement water management plans • Establish mechanisms for representative collaboration of all stakeholders in water resource planning and resource conservation • Build capacity in provincial water agencies in modeling and forecasting	• Human resources to conduct ongoing basin planning (on a permanent basis) • Experts to support the planning process • Representative stakeholders/groups to inform and support basin planning • Financial resources to conduct the planning tasks • Contribution from all sectors and tiers of government with an interest or role in groundwater use or management	Web-based (see earlier) public availability of the following: • Map of water resource planning areas in the Indus basin • A list of water resource assets associated with each planning area • Expert and stakeholder input reports to the development of each plan • Draft (for public consultation) and final plans for each area • Summary information for each plan	• Prioritized schedule with intended delivery dates of plans (various scales) • Evaluation and feedback reports on draft planning area boundaries • Evaluation and feedback reports on draft water resource management plans • Monitoring and evaluation reports of stakeholder engagement (sufficiency and representative)

table continues next page

TABLE D.1. continued

Supporting priorities	Key strategic actions	Required resources	Outcomes	Performance measures
Agricultural water productivity and conjunctive water use	**Technical reform** • Characterize agroecological and socioeconomic zones for options for improved agricultural water productivity • Identify best options for conjunctive water uses in agriculture • Reassess canal duties within and among canal command areas, incorporating the spatial variability of rainfall and evaporative demand • Promote nonwater inputs to increase production with the same level of water use or with reduced water uses • Improve agricultural water management—match irrigation applications to crop water requirements and minimize nonbeneficial evaporative losses • Reduce waterlogging and salinization through improved irrigation practices (reduce overirrigation), better planning of drainage, and adaptation of cropping in saline environments **Policy reform** • Support adoption of high-value–low-water use crops and associated value chains to improve agricultural productivity and farming livelihoods • Reduce perverse policy incentives that promote overuse, or contamination, of groundwater • Promote drainage techniques in waterlogged areas • Invest in new technologies to increase economic benefits from reduced irrigation water uses • Promote research into beneficial agricultural use of saline groundwater • Align agricultural policy with groundwater management policies and establish grounds for necessary enforcement actions **Institutional reform** • Improve capacity of extension services and introduce private service providers increasing groundwater productivity in agriculture • Coordinate with responsible water agencies to maximize responsible water use • Build capacity of the farming communities	• Human and financial resources • Appropriate technologies and methodologies are available and capacity to adapt best practices developed • Relevant, responsive, and well-coordinated institutional setup and corresponding effort • Farmers are willing to participate	• Agricultural water productivity increased • Reclamation of waterlogged and saline areas	• Measurable increased agricultural production per unit of water used within five years • Measurable reduction in land affected by waterlogging and salinity within five years

table continues next page

TABLE D.1. continued

Supporting priorities	Key strategic actions	Required resources	Outcomes	Performance measures
Improved groundwater management and resource conservation	**Technical reform** • Assess recharge and discharge balances for all the critical aquifers and canal commands, ensuring compatibility with surface water planning calculations • Establish sustainable yields at basin level and in water management areas • Determine resource condition indicators for improving groundwater management • Determine optimal water use practices in water management areas to support conjunctive use, reduce depletion, and minimize waterlogging • Reduce groundwater stress in urban areas and adopt rainwater harvesting and artificial recharge of groundwater in urban hotspots • Establish MAR schemes to improve the use of aquifer storage and increase drought resilience of communities • Identify techniques to improve protection of fresh groundwater in coastal areas and strategies to minimize seawater intrusion into coastal aquifers • Prevent uncontrolled discharge into rivers and drains of untreated domestic and industrial effluents • Use computer modeling and graphical techniques to understand current processes and simulate future groundwater conditions **Policy reform** • Review groundwater policy and laws, identify gaps, and update legislation • Mandate the engagement of stakeholders in groundwater management • Develop and enforce water allocation rules for all water sources • Strengthen groundwater protection regulations and take effective action against polluters **Institutional reform** • Assign institutional responsibility for groundwater management • Establish formal coordination mechanisms among the lead agency, other water agencies, and other sectors and with other jurisdictions • Establish reporting mechanisms for state of groundwater and salinity in the basin, including technical, social, economic, and environmental factors • Establish formal mechanism for engagement of stakeholders, ensuring appropriate representation from women, economically disadvantaged people, and minorities	• Adequate human and financial resources • Appropriate technical facilities • Financial and in-kind support for field research • Contribution from experts • Relevant, responsive, and well-coordinated institutional setup • Farmers' participation • Stakeholder engagement • Effective collaboration and contribution from government and private agencies across the water sector, in other sectors, and from other jurisdictions	• Area of groundwater depletion is reduced • Improved groundwater quality • Coastal area vulnerability to saline intrusion is reduced • Users and stakeholders understand the challenges and are engaged in addressing them	• Resource condition indicators tested • Pilot areas demonstrated • Capacity to develop groundwater models for major canal commands in national and provincial agencies • Increased participation of women professionals in groundwater management • Regulatory, legislation, and policy provisions are enforced at all the levels • Annual groundwater status reports for major canal commands

Note: CAPEX = capital expenditure; CCA = cultivable command area; EC = electrical conductivity; MAR = managed aquifer recharge; OPEX = operating expenditure.

SAWI SOUTH ASIA WATER INITIATIVE

GWSP GLOBAL WATER SECURITY & SANITATION PARTNERSHIP

WORLD BANK GROUP

SKU W20018